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FIRED HEATERS: NITROGEN OXIDES EMISSIONS AND CONTROLS

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FIRED HEATERS:

NITROGEN OXIDES EMISSIONS AND CONTROLS

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16. ABSTRACT The report gives results of a study of nitrogen oxide (NOx) emissions from, and controls for, fired heaters. (The petroleum refining and chemical manufacturing industries account for most of fired-heater energy use. An estimated 4600 fired heaters are in operation in these two industries. NOx are formed in fired heaters by two mechanisms: thermal NOx and fuel NOx.) The report gives a brief description of the design and operation of fired heaters. Descriptions of the two major industries with fired heaters and the various heater applications are presented. An estimate is made of the growth in fired heater energy demand and the number of new fired heaters to be built in the next 5 years in these industries. The factors affecting NOx emissions from fired heaters are discussed, and quantitative relationships are presented, where available. Combustion modifications and flue gas treatment controls for NOx emissions are described. Low excess air (LEA) operation and low-NOx burners are discussed in detail. Long-term continuous NOx emissions data for 12 petroleum refinery heaters are presented. Results of a regression model to predict the effect of stack oxygen level on NOx emissions are used to evaluate LEA performance. This study also presents capital and annualized costs for LEA and low-NOx burner controls.

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Heating Equipment	Fuel Oil	Stationary Sources	13A	
Petroleum Refining		Fired Heaters	13H	
Chemical Industry		Chemical Manufacturing	07A	
Combustion		Low Excess Air (LEA)	21B	
Flue Gases		Low NOx Burners		

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ABSTRACT

A brief description of fired heaters design and operation is presented. Descriptions of the major industries with fired heaters and the various heater applications are presented. Estimate is made of the growth in fired heater energy demand and the number of new fired heaters to be built in the next five years in these industries. The factors affecting NO_x emissions from fired heaters are discussed and quantitative relationship presented, where available. Combustion modifications and flue gas treatment controls for NO_x emissions are described. Low excess air (LEA) operation and low-NO_x burners are discussed in detail. Long-term continuous NO_x emissions data for 12 petroleum refinery heaters are presented. Results of a regression model to predict the effect of stack oxygen level on NO_x emissions are used to evaluate LEA performance. Capital and annualized costs are presented for LEA and low-NO_x burner controls.

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SECTION 1

INTRODUCTION

The purpose of this study is to characterize NO_x emissions from fired heaters, identify applicable control techniques, and present the costs associated with these control techniques. Section 2 presents the conclusions and recommendations resulting from this study. Section 3 contains a discussion of the design and operation of fired heaters, a description of the major industries with fired heaters applications, and a discussion of the major parameters affecting NO_x emissions from fired heaters. Section 4 presents NO_x emission control techniques that have been used on fired heaters in commercial applications. These techniques are categorized as either combustion modifications or flue gas treatments. Section 5 presents cost estimates for the major combustion modification control techniques. This report also contains 4 appendices, one of which lists metric conversions since all work has been reported in engineering units.*

A fired heater is a heat transfer device in which heat liberated by the combustion of fuels is transferred to fluids contained in tubes. The major applications of fired heaters are in the petroleum refining and chemical manufacturing industries. There are two basic functional categories of fired heaters applications. The simplest category contains those heaters designed to increase the temperature of a feedstock stream prior to additional processing. Distillation column feed preheaters and reboilers are an example of this category. The second major fired heater category consists of fired reactors, in which high-temperature chemical reactions are carried out in the tubes of the heater. These include steam-hydrocarbon reformers used in ammonia and methanol manufacturing, and pyrolysis furnaces used in ethylene manufacturing. The fuels used for fired heaters include natural gas, refinery gas, and various grades of fuel oil.

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*It is EPA policy to report measurements in the International System (SI) of units. For clarity of presentation, units used in this report are those commonly used in engineering calculations in the U.S. Conversion factors are presented in Appendix D.

Oxides of nitrogen are formed in fired heaters by two mechanisms: thermal NO_x formation and fuel NO_x formation. Thermal NO_x is the result of the reaction between atmospheric nitrogen and oxygen, while fuel NO_x is the result of the reaction between fuel-bound nitrogen and oxygen. The various heater designs and operating parameters that affect NO_x emissions are described in this study. When available, quantitative data are presented from previous studies showing the relationship between these parameters and NO_x emissions.

This study also summarizes short-term (1 - 2 hours) NO_x emissions data for about 150 fired heaters in various applications. While most of these data were collected and reported in previous studies, some were obtained directly from various plants specifically for this study. In addition, continuous long-term NO_x emissions data were obtained in this study for 12 heaters at three petroleum refineries. Two of these refineries continuously monitor NO_x emissions for regulatory compliance purposes. Data on one heater at the third refinery was collected over a 45 day period in a previous EPA study. These data included from about 540 to 3,400 hourly data points for each heater. The hourly measurements included NO_x emission rates, stack oxygen levels, fuel firing rate, fuel gas hydrogen content, and the energy basis ratio of gas to oil (where applicable). These data were analyzed statistically to quantify the effect of stack oxygen level on NO_x emissions. Using the results of the regression analysis, NO_x levels were predicted for the 12 heaters at various oxygen levels. This allowed for a determination of the effectiveness of low excess air (LEA) operation on NO_x emissions as well as allowed comparison of NO_x emissions from different heater/burner types at the same stack oxygen level.

The two major combustion modification control techniques discussed in this report include LEA operation and low-NO_x burners. LEA operation of fired heaters can be achieved by (1) manual damper control systems based on oxygen monitoring and increased operator attention and (2) automatic damper control system based on oxygen monitoring (and/or other process monitoring) and microprocessor control. Low-NO_x burners can be used alone or in combination with LEA operation. The major type of low-NO_x burners is the staged air burner which employs staged air addition to the fuel stream. A more recent type of low-NO_x burner is the staged fuel burner which also uses staged combustion to reduce NO_x formation, but with reversed staging principle.

Cost estimates were made for LEA and low-NO_x burner controls. The energy credits associated with LEA operation were also estimated.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

2.1 CONCLUSIONS

The following conclusions were made in this study:

- The petroleum refining and petrochemical industries account for the major fired heater use. The estimated fired heater energy consumption in the petroleum refining industry in 1985 is approximately 2.2 x 10^{15} Btu/yr. The 1985 chemical industry fired heater energy consumption is estimated to be 6.8 x 10^{14} Btu/yr.

- The annual increase in fired heater energy consumption in the petroleum refinery industry is estimated to be 14.6 x 10^{12} Btu/hr. It is projected that approximately 80 new fired heaters will be built in the petroleum refining industry over the next 5 years.

- The annual increase in fired heater energy consumption in the chemical industry is estimated to be about 14.7 x 10^{12} Btu/hr. About 100 fired heaters are projected to be built in the chemical industry over the next 5 years.

- Almost 100 percent of the fired heater applications in the petroleum refining industry are low and medium temperature heaters. About 81 percent (energy basis) of the fired heater applications in the chemical industry are high temperature heaters (ethylene pyrolysis furnaces and steam-hydrocarbon reformers).

- The major heater design parameters affecting NO_x emissions are fuel type (i.e., N_2 content of the fuel), burner type, use of combustion preheat, and firebox temperature.

- The major heater operating parameters affecting NO_x emissions are excess air level, degree of combustion air preheat, and oil/gas ratio for heaters firing combined fuel.

- The control techniques that have been used on fired heaters in commercial applications include low excess air (LEA) operation, low-NO_x burners, staged air lances, flue gas recirculation, selective catalytic reduction, and selective noncatalytic reduction.

- LEA control systems are applicable to all fired heaters. Manual and automatic damper control systems designed to reduce excess air levels can be used with natural or mechanical draft and with gas, oil, or gas/oil combination burners.

- At least 55 fired heaters are presently using automatic LEA control systems and many others use manual LEA control systems based on oxygen monitoring.

- The target stack oxygen level for most heaters operating with LEA is 2 - 3 percent. The lowest long-term average oxygen level for heaters in the data base was 2 percent.

- The average stack oxygen level for about 180 heaters for which data were obtained in this study was 5.5 percent.

- Statistical analysis of continuous long-term NO_x emissions data for 12 petroleum refinery heaters indicated an average of 9 percent reduction in NO_x emissions per percent reduction in stack oxygen level. The individual reduction in NO_x emissions ranged from 4.4 percent to 16.4 percent.

- No effect of burner or draft type was found on the NO_x/O_2 relationship.

- Two major burner vendors have indicated that about 50 to 65 percent of their new burner sales are low-NO_x burners.

- No conclusion about the performance of low-NO_x burners could be derived from the continuous monitoring data because other design differences between heaters obscure the effect of low-NO_x burners.

- Test-scale data from burner vendors indicate that NO_x emission reduction with the use of staged air burners ranges from 38 to 40 percent compared to conventional burners. NO_x emission reduction associated with the use of staged fuel burners ranges from 70 to 72 percent compared to conventional burners.

- Staged combustion air lances have been demonstrated for 15 days on a natural gas-fired, natural draft heater. The same heater was retrofitted with forced draft and tests were conducted for 30 days with staged air lances.

- Regression modeling results showed that at a fixed stack oxygen level natural draft air lances reduced NO_x emissions by 50 to 60 percent relative to baseline (without staged air lances). Forced draft air lances further reduced emissions by 30 to 50 percent relative to natural draft air lances.

2.2 RECOMMENDATIONS

The continuous long-term NO_x emissions data analyzed in this study showed a very strong correlation between stack oxygen levels and NO_x emissions for all heaters. However, these data were not suitable for evaluating the effects of other heater design and operating parameters on NO_x emissions. For example, at a given stack oxygen level, the heaters with low-NO_x burners showed higher average NO_x emissions than the heaters with conventional burners in the long-term data base. This was because other heater parameters obscured the effect of low-NO_x burners. The performance of low-NO_x burners can only be determined by testing and comparing the NO_x emission levels for conventional and low-NO_x burners in the same heater. While such tests have been conducted on test-scale heaters by burner vendors, no data are available from commercial heaters. It is recommended that a 15-day test be conducted on a commercial heater under similar operating conditions during tests with conventional and low-NO_x burners.

There were two combination oil/gas-fired heaters in the long-term data base. These heaters fired up to 30 percent oil on an energy basis. The data analysis did not show the average NO_x emissions from these heaters to be statistically different from the 100 percent gas-fired heaters. Once again it is suspected that other heater parameters obscured the effect of oil firing. Test-scale data have previously shown a strong relationship between the nitrogen content of the fuel (and hence percent oil-fired) and NO_x emissions. Since most new burners sold presently have capability to fire both fuels, oil firing can be a significant source of NO_x emissions from fired heaters. It is recommended that a 15 to 30-day test be conducted on a commercial combination oil/gas-fired heater. The test should be conducted with various fractions (energy basis) of oil firing to evaluate the effect of increasing oil fraction on NO_x emissions.

No long-term continuous NO_x emissions data were available for high temperature heaters. Firebox temperature has been shown to have a significant effect on NO_x emissions. However, the major types of high temperature heaters have a design feature which may have an obscuring effect on NO_x emissions. Both pyrolysis furnaces and steam-hydrocarbon reformers require extremely uniform temperature distribution along the tube length. To achieve this, these heaters generally have a large number of small burners distributed uniformly along the walls of the heater. Uniform heat distribution has been reported to impede NO_x formation. The short-term spot test data obtained in this study for high temperature heaters show a wide range of NO_x emissions. In order to compare the long-term average NO_x emissions for the high temperature chemical industry heaters with the low and medium temperature petroleum refinery heaters, it is recommended that a 15-day test be conducted on a high temperature heater operating under low excess air (LEA) conditions.

Finally, all continuous long-term NO_x emissions data analyzed in this study were for heaters operating with manual LEA control. In order to determine the minimum LEA level achievable, it is recommended that a 7-day test be conducted on a heater using an automatic LEA control system.

SECTION 3
FIRED HEATERS DESIGN, OPERATION, AND EMISSIONS

This section contains a description of the design and operation of fired heaters, a description of the major industries with fired heaters applications, and a discussion of NO_x emissions from fired heaters. Background information on fired heaters is presented in Section 3.1, and the factors affecting NO_x emissions from fired heaters are discussed in Section 3.2.

3.1 BACKGROUND INFORMATION

3.1.1 Definition and Types of Fired Heaters

A fired heater is a heat transfer device in which heat liberated by the combustion of fuels is transferred predominately by radiation and secondly by convection to fluids (i.e., gases and liquids) contained in tubes. Fired heaters are found primarily in the petroleum refining (SIC Code 2911) and petrochemical industries (included in the chemical and allied products major group, SIC code 28) with minor applications in the fibers, iron and steel, gas processing and other industries. They are known interchangeably within these industries as process heaters, process furnaces, and direct-fired heaters.

Fired heaters are used in high temperature heat transfer applications for which steam heating is impractical. In general, this includes processes in which heat must be transferred at temperatures in excess of about 400°F. There are two basic functional categories of fired heater applications. The simplest category contains those heaters designed to increase the temperature of a feedstock stream or heat transfer fluid prior to additional processing or use. In some applications, the feedstock stream can become partially or totally vaporized as the result of heating. Distillation column feed preheaters and reboilers, reactor feed preheaters, hot oil furnaces, and viscous fluid heaters are included in this group. The second major fired heater category consists of fired reactors, in which high-temperature chemical reactions are carried out in the tubes of the firebox. These include steam-hydrocarbon reformers used in ammonia and methanol manufacturing, pyrolysis furnaces used in ethylene manufacturing, and visbreaking and thermal cracking units employed in refinery operations.

Fired heaters vary in size according to the unit heat requirements of the particular application and the production capacity of the plant at which the heater is found. Heater size is commonly defined in terms of the design heat absorption capacity (heat duty), which ranges from about 0.5 to 1,000 MMBtu/hr. A typical fired heater falls into the 10 to 350 MMBtu/hr size range.[1] An alternate definition of fired heater size based on fuel firing rate instead of heat absorption capacity would be preferable when discussing NO_x emissions. However, this definition is not generally used.

The fuels used for fired heaters include natural gas, refinery gas, and various grades of fuel oil. Gas fuels account for about 90 percent of the fired heater energy consumption, with oil fuels accounting for the remaining 10 percent.[2] Gas and oil are often fired simultaneously in the same heater. Coal is not used as a fired heater fuel because of problems associated with ash removal, corrosion, slagging, and flame shape in coal combustion. These factors reduce the degree of heat transfer control achievable in coal-fired units below the level required for fired heater applications.

3.1.2 Physical Description

There are many variations in the design and construction of fired heaters. However, most heaters contain the basic features shown in Figure 3-1. The radiant section of a fired heater consists of the burner(s), the firebox, and a row of tubes containing the process fluid. The majority of the heat transfer to the feedstock occurs in the radiant section of the heater by flame radiation. Most heaters also contain a convective section in which heat is recovered from the hot combustion gases

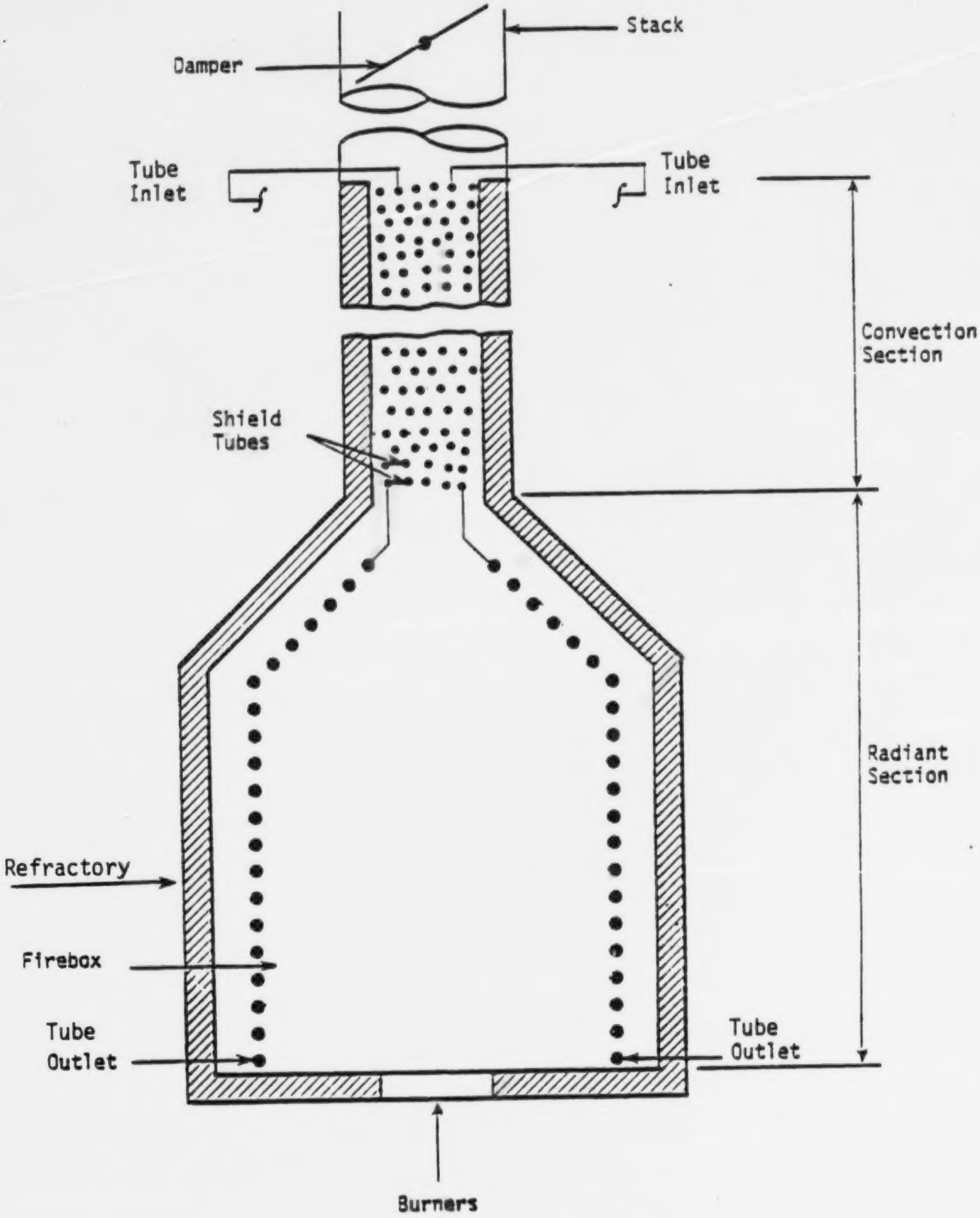

Stack
Damper
Tube Inlet
Tube Inlet
Convection Section
Shield Tubes
Radiant Section
Refractory
Firebox
Tube Outlet
Tube Outlet
Burners

Figure 3-1. Cross-section of a typical horizontal cabin-type fired heater.

by convective heat transfer to the feedstock. Other flue gas heat recovery systems used with fired heaters include combustion air preheaters, waste heat boilers, feedwater preheaters, and hot oil loops. In addition to the radiant section and the convection section, fired heaters contain auxiliary equipment such as stack dampers and fans to control the flow of combustion air to the firebox.

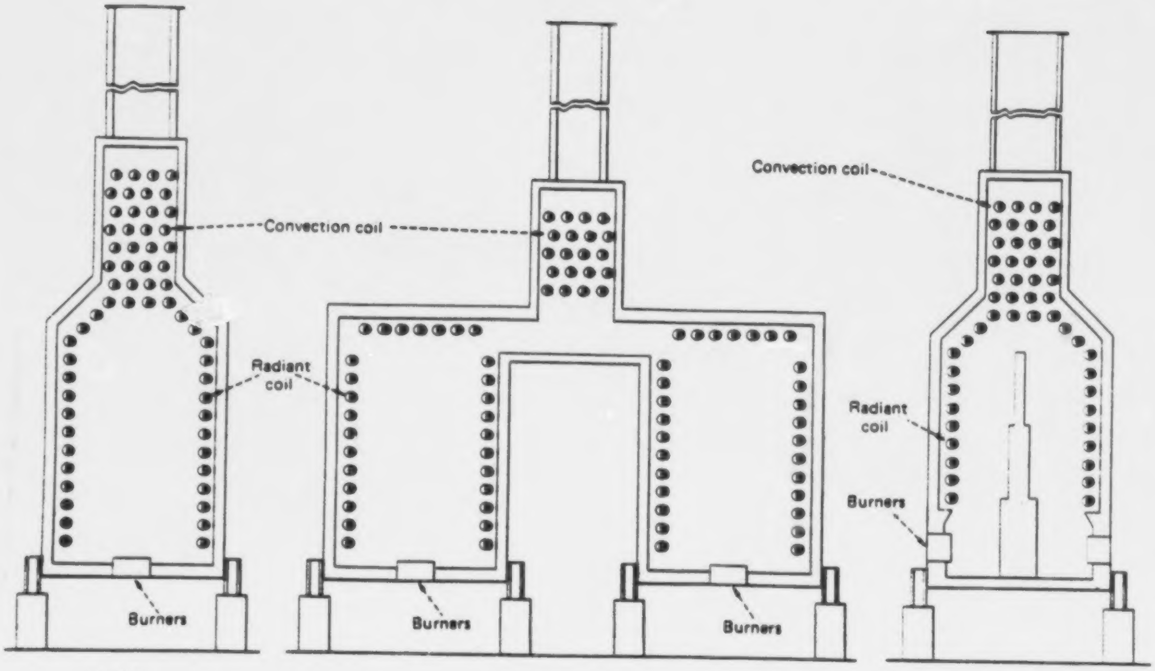
3.1.2.1 Firebox and Tube Orientation--

The principal classification of fired heaters is based on the shell shape and the orientation of the radiant tubes. The convection tubes are oriented horizontally while the radiant tubes may be oriented either horizontally or vertically. Several types of fired heater designs are shown in Figure 3-2. Each type is engineered to achieve a particular combination of size and heat transfer characteristics unique to a specific application. For example, the arbor or wicket type of fired heater is a specialty design that is suited for heating large flows of gas under conditions of low pressure drop.

The majority of new fired-heater installations are either of the vertical tube/cylindrical shell design with crossflow convection or the older horizontal tube/cabin shell design with crossflow convection. These configurations represent economical, high-efficiency designs that require minimal plot area. They typically range in absorbed heat duty from about 10 to 200 MMBtu/hr.

3.1.2.2 Method of Combustion Air Supply--

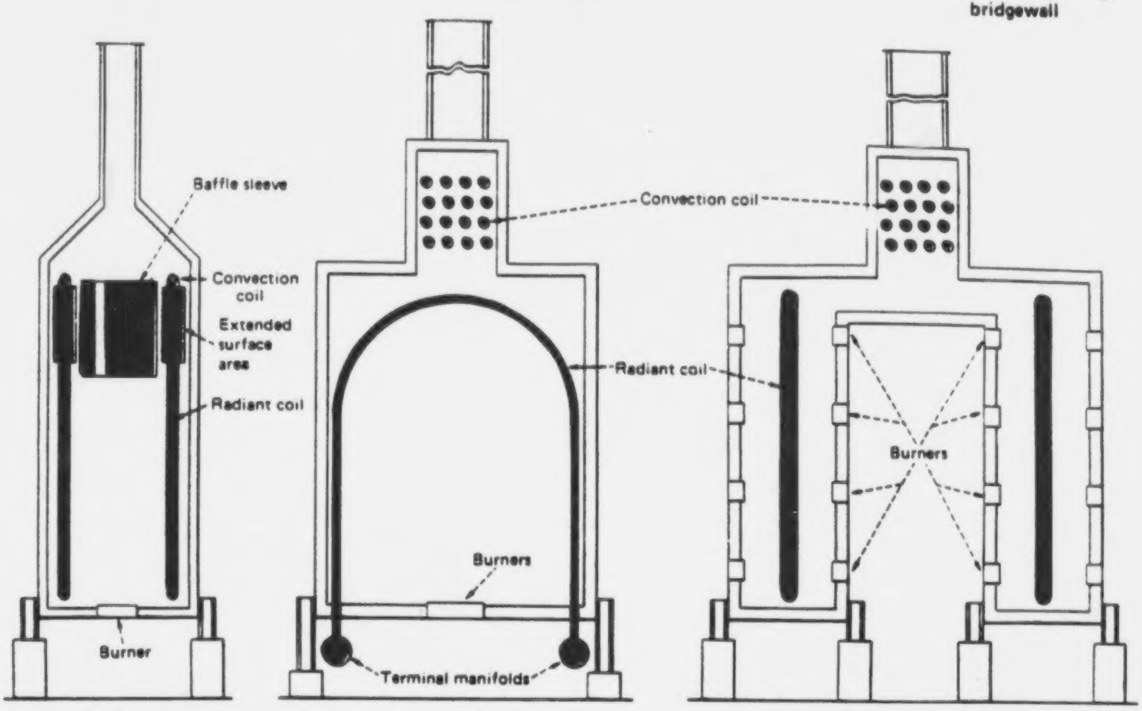
Two basic methods of combustion air supply are available for fired heaters, natural draft and mechanical draft. Natural draft heaters make use of the draft (sub-atmospheric pressure) produced by the density difference between the hot flue gases in the heater stack and the cooler ambient air to induce combustion air flow into the burners. The amount of draft measured in the region directly below the convection section of a natural draft heater is typically on the order of 12 pascals (0.05 inches of water).


Convection coil
Radiant coil
Burners
Convection coil
Radiant coil
Burners
Burners
Convection coil
Radiant coil
Burners

a. Cabin

b. Two-cell box

c. Cabin with dividing bridgewall


Baffle sleeve
Convection coil
Extended surface area
Radiant coil
Burner
Convection coil
Radiant coil
Burners
Terminal manifolds
Burners

d. Vertical-cylindrical with integral convection section

e. Arbor or wicket type

f. Vertical-tube, single-row, double-fired

Figures 3-2. Examples of radiant section tube orientations in fired heaters.[3]

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Mechanical draft heaters use fans to supply the combustion air to the burners. Three types of mechanical draft systems are available: forced draft, induced draft, and balanced draft. The three types are distinguished by the position of the fan(s) relative to the heater unit. In forced draft heaters the fan is located upstream of the firebox, and combustion air is supplied under positive pressure to the burner(s). The air pressure supplied to the burners in a forced draft heater is typically in the range of 1.5 to 2.4 kilopascals (6 to 10 inches of water).[4] The combustion chamber and all other parts of the forced draft heater operate under negative pressure, and flue gas is removed by the stack effect. In induced draft heaters the fan is located downstream of the firebox, and the negative pressure created within the heater induces the flow of combustion air. Balanced draft heaters use both forced and induced draft fans to control the flow of combustion air. Most mechanical draft heaters currently in use are forced or balanced draft type.

From operational and economic standpoints, there are both advantages and disadvantages to the use of either natural or mechanical draft heaters. Natural draft systems are simpler since they do not require the fans and other auxiliary equipment associated with mechanical draft systems. However, natural draft does not allow for precise control of combustion air supply and requires higher excess air levels than mechanical draft for a given degree of flame stability. Because of the ability to operate at lower excess air levels, mechanical draft heaters are more energy efficient than natural draft heaters. Mechanical draft heaters are also more versatile than natural draft heaters with respect to the use of alternate sources of combustion oxygen, such as gas turbines exhaust, and the use of combustion air preheat.

3.1.2.3 Use of Combustion Air Preheat--

Combustion air preheaters are often used in conjunction with mechanical draft to improve the thermal efficiency of fired heaters. Natural draft heaters cannot utilize combustion air preheat because of the pressure drop associated with the recuperative heat exchange system. Figure 3-3 illustrates

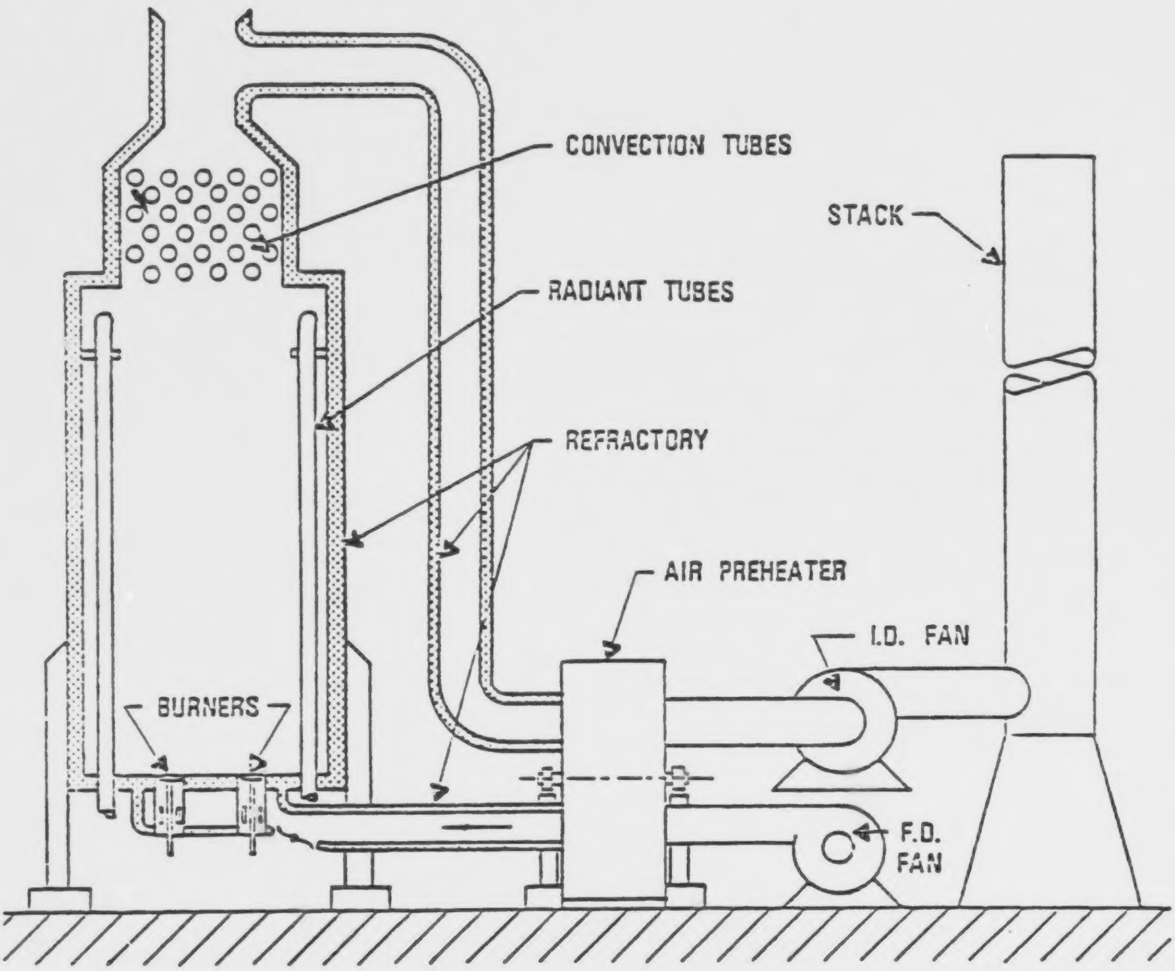
CONVECTION TUBES
STACK
RADIANT TUBES
REFRACTORY
AIR PREHEATER
I.D. FAN
BURNERS
F.D. FAN

Figure 3-3. Vertical cylindrical balanced draft type process heater with air preheater. Adapted from reference 5.

a typical process scheme for a mechanical draft fired heater with combustion air preheat. Heat is transferred from the hot flue gas to the combustion air in the preheater, thereby reducing the exit temperature of the flue gas and increasing the thermal efficiency of the fired heater. A mechanical draft heater with a convection section and a combustion air preheater typically has a flue gas exit temperature of 350°F and can have a thermal efficiency as high as 92 percent (LHV),[6] while a mechanical draft heater with a convection section but no preheater typically has a flue gas exit temperature of 600°F and a thermal efficiency of 85 percent (LHV). The thermal efficiency of a natural draft heater is about 70 percent. The increased efficiency of fired heaters equipped with combustion air preheat makes preheat economically feasible for new heaters larger than about 30 MMBtu/hr.

3.1.2.4 Burner Types and Location--

There are many types of burners currently used in fired heaters. Four common designs are shown in Figure 3-4. The burner types selected for a particular application depends on several factors, including process heat flux requirements, fuel type, and draft type. Burners must be chosen such that the flame shape and radiant heat flux produced by combustion are compatible with the mechanical configuration of the heater's radiant section and the thermal requirements of the process. Similarly, the number of burners in a heater and the location of the burners may be determined by the heater application.

Burners can be designed to provide various types of flames. The most common flame shapes are flat and conical. The intensity of a given flame type can be adjusted in accordance with the heat flux requirements of the process under consideration. For example, long conical flames are often used to provide a uniform heat flux in the radiant section of a heater. Short, flat flames are used in high temperature applications such as ethylene pyrolysis furnaces by virtue of their ability to heat the refractory firebox lining to incandescence. The refractory material radiates heat back to the fluid circulating in the tubes, thereby providing a uniform source of high

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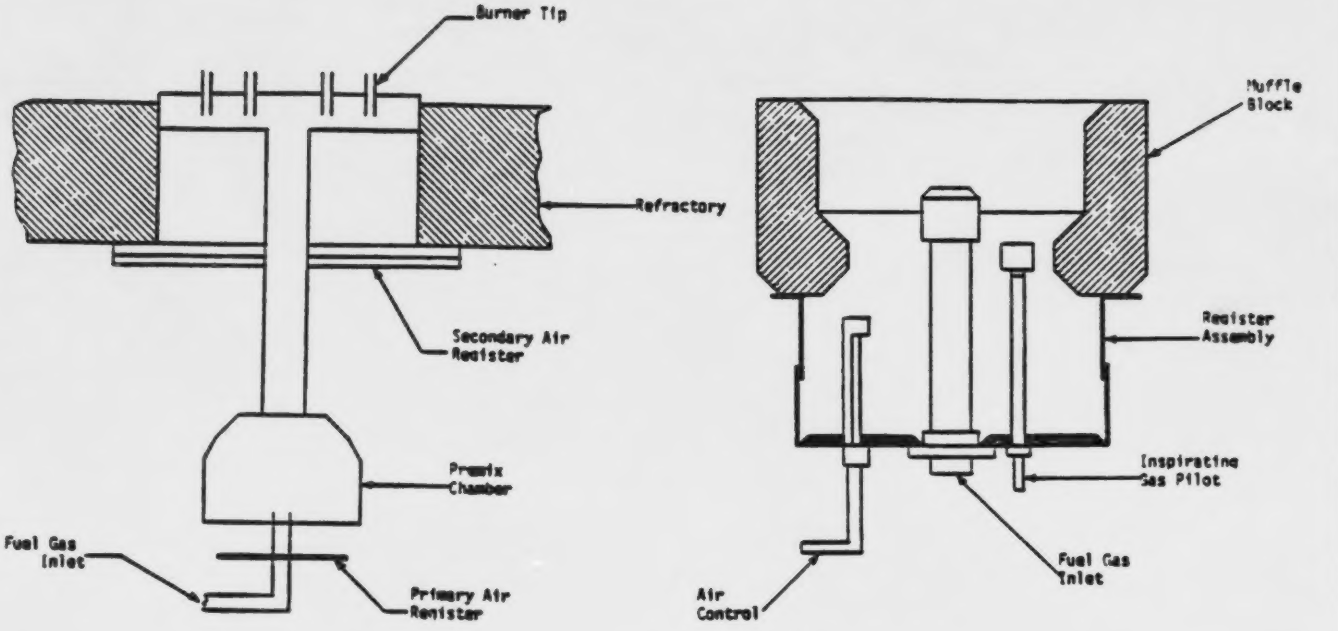
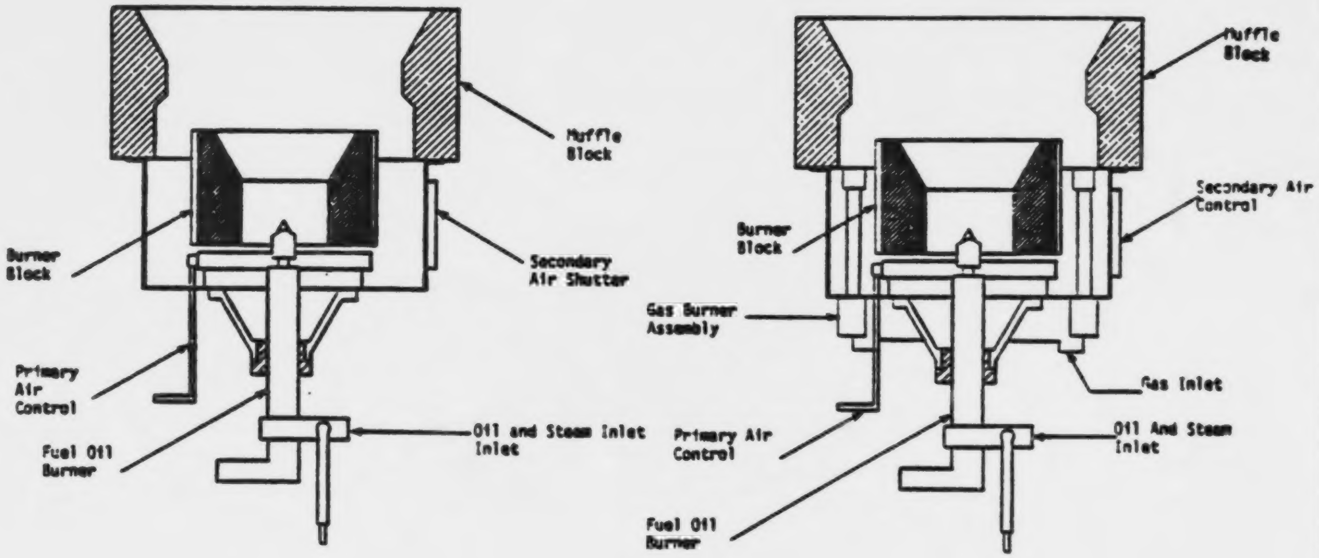

Burner Tip
Refractory
Secondary Air Register
Premix Chamber
Fuel Gas Inlet
Primary Air Register
Muffle Block
Register Assembly
Inspirating Gas Pilot
Fuel Gas Inlet
Air Control

a. Premix Burner

b. Raw Gas Burner


Muffle Block
Burner Block
Secondary Air Shutter
Primary Air Control
Fuel Oil Burner
Oil and Steam Inlet
Muffle Block
Secondary Air Control
Burner Block
Gas Burner Assembly
Gas Inlet
Primary Air Control
Oil And Steam Inlet
Fuel Oil Burner

c. Oil Burner

d. Combination Oil and Gas Burner

Figure 3-4. Typical burners by type of fuel burned.

temperature heat transfer. In these and other instances, the flame type and flame intensity required for a particular application represent important criteria with regards to burner selection.

Fuel compatibility is another important criterion affecting burner selection and design. Burners may be designed to fire various types of gas and oil fuels, as well as gas/oil combinations. In some cases burners are designed specifically for a particular fuel composition, such as low-Btu fuel gas or residual fuel oil. The trend in industry is to install burners with dual firing capabilities to maximize the operational flexibility of the heater.

Gas-fired burners can be placed into three broad categories: raw gas burners, premix burners, and high intensity burners. Raw gas burners receive fuel gas from the gas manifold without any premixing of combustion air. Mixing of gas and air occurs in the combustion zone at the burner tip, and the addition of either air and/or gas can be staged to control combustion.[7] Staged combustion raw gas burners (low NO_x burners) represent a recent design that has been developed with the specific intent of lowering NO_x emissions relative to those of conventional unstaged raw gas burners. Low NO_x burners are further discussed in Section 4.

Premix burners receive a mixture of combustion air and fuel at the burner tip. Air is inspirated into the fuel gas stream by the mechanism of jet entrainment as the gas expands through an orifice located upstream of the burner tip. The primary air inspirated into the fuel gas stream usually accounts for 50 to 60 percent of the air required for complete combustion, although 100 percent premix burners also exist. The remaining air is introduced at the burner tip through secondary air registers.[7]

High intensity gas-fired burners are designed to fire low-Btu fuel gas that is unsuitable for conventional burners. They are forced draft burners that require a relatively high pressure air supply (i.e., as high as 20 inches of water) to sustain combustion. A strong vortex is generated in the combustion zone by passing the combustion air through a series of "spin vanes," which leads to a high degree of fuel-air mixing in the combustion zone. High intensity burners are noted for extremely compact flames and low excess air operation.[7]

Oil-fired burners vary primarily in the method of oil atomization prior to combustion. Steam is the most common atomizing medium, but occassionally air atomization or mechanical atomization are used. Most oil-fired burners are designed with a double pipe system that injects the steam and oil into a mixing chamber prior to combustion. The steam and finely dispersed oil are sent through a series of orifices into a turbulent air stream where combustion occurs. Staged combustion oil-fired burners (low NO_x burners) are available that produce lower NO_x emissions than conventional oil-fired burners. High-intensity oil-fired burners are also used for firing heavy oils with a high carbon to hydrogen ratio. These fuels require special burners to avoid excessive soot formation.[7]

Combination burners are designed to burn all oil, all gas, or any combination of oil and gas simultaneously. These burners generally have a double block design featuring a single oil gun in the center of an array of gas nozzles. When a heater with combination burners is fired by both gas and oil, there are two options for the distribution of the two fuels to the individual burners. Frequently some of the burners are fired by 100% gas and the remainder are fired by 100% oil. Alternatively, one or more of these burners can be baseloaded with one fuel, and the other fuel can be fired simultaneously in the same burners to account for the remainder of the heat load. Combination fuel burners add to the flexibility of the heater when the characteristics of the fuel are variable (e.g. refinery gas).

Burner location varies considerably among existing designs. Burners can be fired from the top, wall, or floor of the heater. Wall and floor fired units are the most common as they are both versatile and efficient. In particular, floor fired burners integrate well with the use of combustion air preheat, liquid fuels, and alternate sources of combustion oxygen such as gas turbine exhaust. Down-fired burners are frequently used for steam-hydrocarbon reformer furnaces because of the compatibility of this arrangement with the kinetics of the reforming reactions.[7]

The number of burners in a heater may vary from one to more than one hundred, depending on the heater application. The average number of burners for existing natural draft heaters is estimated to be approximately 24. For mechanical draft heaters with ambient combustion air and preheated combustion air, the average number of burners per heater is approximately 20 and 14, respectively.[8] Small numbers of burners are desirable from the standpoint of simplicity and compatibility with combustion air preheat, but multiple burner heaters are more effective in providing a uniform heat flux distribution within the firebox. The ethylene pyrolysis furnace is an example of a heater design utilizing a large number of small burners to provide even heating.

3.1.3 Fired Heater Operation

To achieve the desired heat transfer performance from a fired heater under conditions of changing heat duty and/or fuel composition, various heater parameters can be adjusted. This may be necessary to maintain a certain process fluid outlet temperature, as in crude oil heaters, or to provide a uniform high temperature heat flux, as in ethylene pyrolysis furnaces. Heaters may also be adjusted to optimize thermal efficiency and/or to control pollutant emissions. The most common process control loop used for fired heaters is based on temperature control of the outlet process fluid. The input fuel flow rate is automatically adjusted to compensate for deviations from the set point charge outlet temperature.[9] A schematic diagram of this type of system is shown in Figure 3-5 for a natural draft heater. In addition to fuel flow rate, the parameters available for heater operational control are heater draft and excess air.

Heater draft and excess air can be varied by adjusting the stack damper, the burner air registers, the fan speeds (forced draft), and the fan dampers (forced draft). In order to insure stable, safe heater operation it is desirable to maintain a slight negative pressure at all points within the heater. Due to the economic benefits of energy conservation it is becoming increasingly important to operate heaters under conditions of low excess air. Thus, a heater must be controlled to simultaneously maintain the proper draft and low excess air. Stack and fan damper adjustments are the primary means of draft and excess air control commonly exercised under

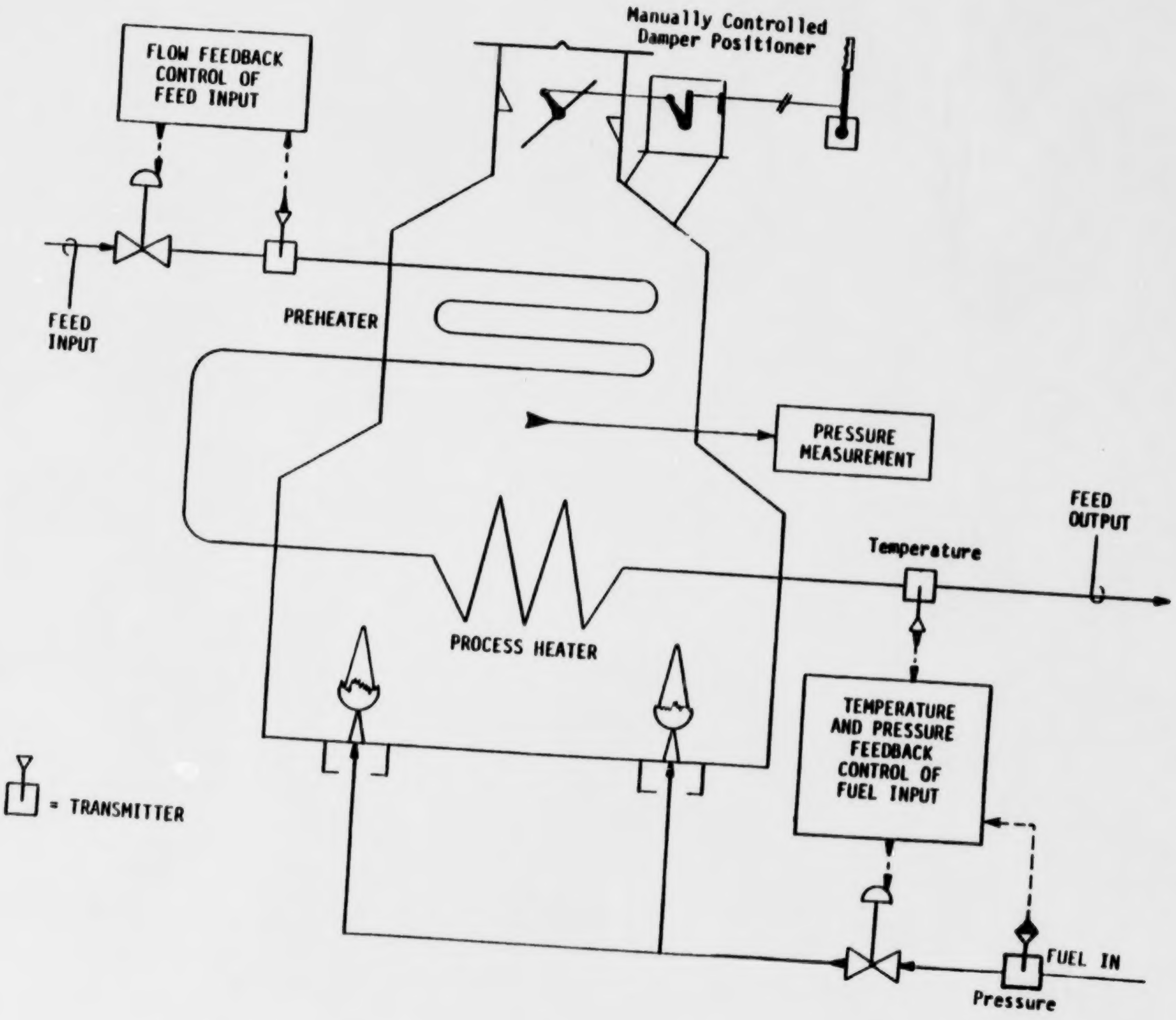

FLOW FEEDBACK CONTROL OF FEED INPUT
Manually Controlled Damper Positioner
FEED INPUT
PREHEATER
PRESSURE MEASUREMENT
FEED OUTPUT
Temperature
PROCESS HEATER
TEMPERATURE AND PRESSURE FEEDBACK CONTROL OF FUEL INPUT
= TRANSMITTER
FUEL IN
Pressure

Figure 3-5. Conventional process control for a natural draft heater.

actual operating conditions. The relationships of heater draft and excess air to stack damper and burner register adjustment are shown in Table 3-1.

Dampers are usually operated with a manually controlled pneumatic linkage or a mechanical damper positioner of the gear or pulley type. Automatic damper controls are available in which the position of the damper is adjusted according to the deviation of the measured excess oxygen level from the desired (i.e., setpoint) level. These and other automatic low excess air (LEA) combustion control systems are discussed in Section 4.1. Heightened awareness of energy cost savings associated with low excess air operation is expected to result in an increase in the number of heaters employing automatic excess air control systems.

In contrast to fuel flow rate and damper position, burner air register adjustments must be made manually. Although it has been suggested that burner register adjustment provides the most effective and safe means of excess air control, register adjustment is not generally used.[10] In most cases the registers are pre-set at an optimal position, and minor adjustments in excess air are made using the stack and/or fan dampers.

3.1.4 Application of Process Heaters in the Petroleum Refining and Chemical Industries

On an energy basis, the petroleum refining and petrochemical industries account for a large fraction of the total fired heater use. The fired heater applications within these industries are identified and discussed below.

3.1.4.1 Petroleum Refining Industry--

Petroleum refineries (SIC 2911) convert crude oil into useful products such as transportation fuels, lubricating oils, and chemical feedstocks. As of January 1, 1985, there were 191 operating refineries in the United States with a capacity to process 15.1×10^6 barrels of crude oil per calendar day. These refineries range in size from 4,000 barrels per calendar day to 494,000 barrels per calendar day, with the mean size being 79,000 barrels per calendar day.[11] The statewide distribution of refinery capacity in the United States is summarized in Table 3-2. The states with the highest

TABLE 3-1. RELATIONSHIP OF STACK DAMPER AND BURNER AIR REGISTER ADJUSTMENT TO HEATER DRAFT AND OXYGEN LEVELS

Adjustment Levels	Effect on Draft	Effect on O_2
Stack Damper Open	Increase	Increase
Stack Damper Close	Decrease	Decrease
Air Register Open	Decrease	Increase
Air Register Close	Increase	Decrease

TABLE 3-2. DISTRIBUTION OF THE PETROLEUM REFINING INDUSTRY BY STATE AS OF JANUARY 1, 1985[11]

State	Number of Refineries	Crude Capacity (Barrels Per Calendar Day)
Texas	33	4,145,900
California	30	2,265,098
Louisiana	16	2,188,793
Illinois	8	946,000
Pennsylvania	8	658,700
Ohio	5	515,700
New Jersey	5	503,000
Indiana	5	431,300
Oklahoma	5	374,000
Washington	7	410,550
Mississippi	5	362,400
Kansas	7	338,000
Others (22 States)	57	1,996,821
Total U.S.	191	15,136,262

refining capacities are Texas, California, and Louisiana. They account for approximately 41 percent of the domestic refineries and 57 percent of the domestic refining capacity.

As shown in Figure 3-6, distillation units are used to perform the initial separation of the crude oil into several fractions. These fractions serve as the feedstocks for secondary processes that vary depending on the fraction type and on the desired product. A representative refinery product slate is shown in Table 3-3 that indicates the approximate breakdown (volume basis) of final products at a typical refinery.[12] Table 3-4 summarizes the refinery processes requiring fired heaters and indicates the heater type corresponding to each application. The predominant use for fired heaters in the petroleum refining industry is as a preheater for various operations such as distillation, catalytic cracking, hydroprocessing, and hydroconversion.

The number of fired heaters used at a refinery varies with the complexity of the facility. Large integrated refineries can have as many as 100 heaters, while small topping refineries can have as few as 4 heaters. The total number of fired heaters in the petroleum refinery industry was estimated in a 1980 API Publication to be about 3,200.[14]

The estimated energy consumption of several direct-fired processes in the petroleum refining industry is shown in Table 3-5 for 1973. The total fired heater energy consumption was 2.0×10^{15} Btu/yr in 1973. The American Petroleum Institute reported that refinery fired heater energy consumption in 1985 is estimated to be approximately 2.2×10^{15} Btu/yr.[15]

The existing refinery fired heater population consists predominantly of natural draft heaters. As shown in Table 3-6 the estimated draft type distribution on an energy basis for existing heaters is: natural draft, 89.6 percent; mechanical draft without preheat, 8.0 percent; and mechanical draft with preheat, 2.4 percent. The mechanical draft heaters tend to be larger than the natural draft heaters. The mean size of all refinery fired heaters is 72 MMBtu/hr while the mean size of mechanical draft heaters is about 110 MMBtu/hr. The size distribution of the refinery fired heater population as a whole is shown in Figure 3-7 for both an energy and a number-of-heaters basis. Table 3-6 and Figure 3-7 are based on data presented in Reference 20.

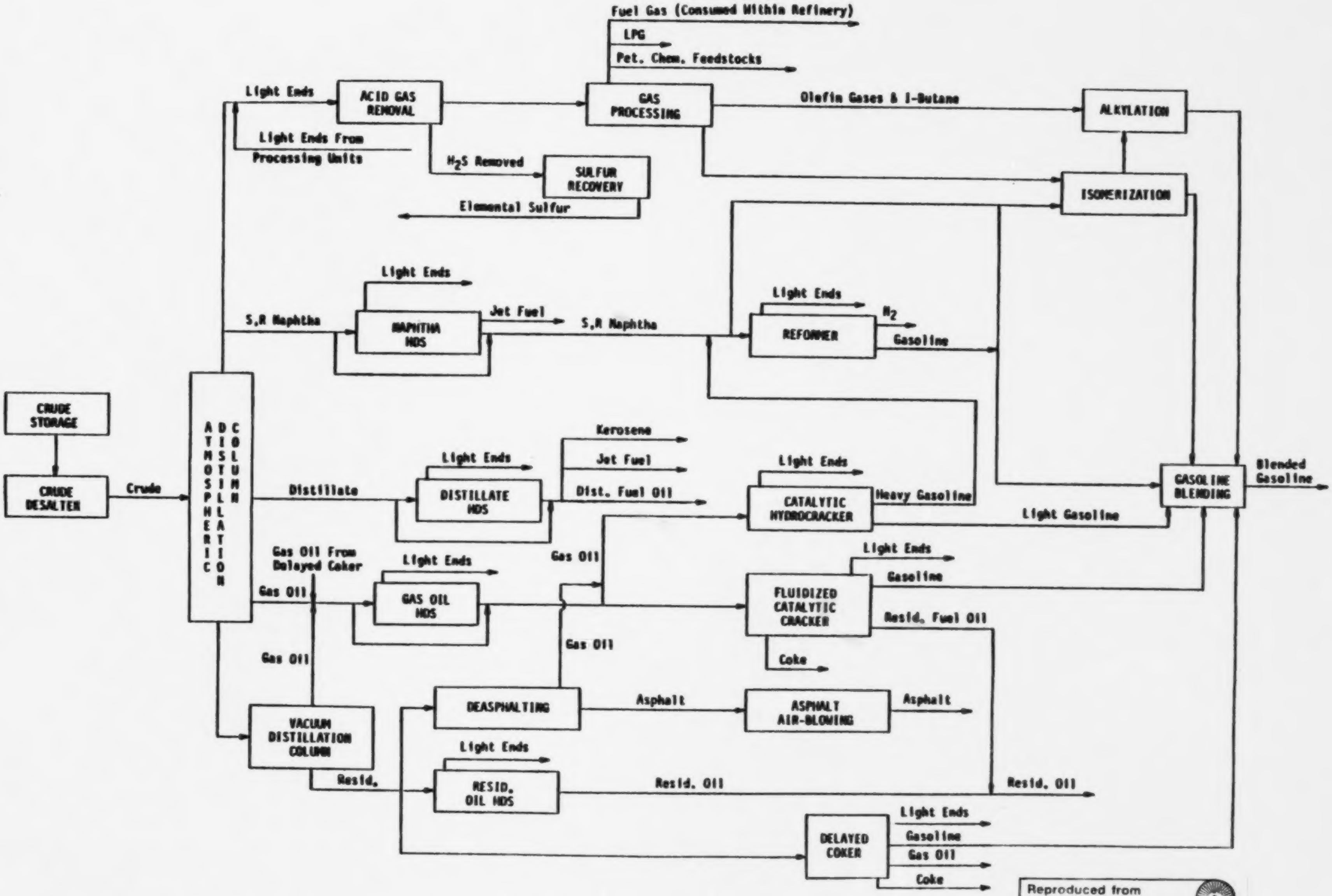

CRUDE STORAGE
CRUDE DESALTER
Crude
ATMOSPHERIC DISTILLATION COLUMN
Light Ends
ACID GAS REMOVAL
Light Ends From Processing Units
H_2S Removed
SULFUR RECOVERY
Elemental Sulfur
GAS PROCESSING
Fuel Gas (Consumed Within Refinery)
LPG
Pet. Chem. Feedstocks
Olefin Gases & I-Butane
ALKYLATION
ISOMERIZATION
S,R Naphtha
Light Ends
NAPHTHA HDS
Jet Fuel
S,R Naphtha
Light Ends
REFORMER
H_2
Gasoline
Distillate
Light Ends
DISTILLATE HDS
Kerosene
Jet Fuel
Dist. Fuel Oil
Light Ends
CATALYTIC HYDROCRACKER
Heavy Gasoline
Light Gasoline
GASOLINE BLENDING
Blended Gasoline
Gas Oil From Delayed Coker
Gas Oil
Light Ends
GAS OIL HDS
Gas Oil
Gas Oil
Light Ends
Gasoline
FLUIDIZED CATALYTIC CRACKER
Resid. Fuel Oil
Coke
Gas Oil
VACUUM DISTILLATION COLUMN
DEASPHALTING
Asphalt
ASPHALT AIR-BLOWING
Asphalt
Resid.
Light Ends
RESID. OIL HDS
Resid. Oil
Resid. Oil
DELAYED COKER
Light Ends
Gasoline
Gas Oil
Coke

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Figure 3-6. Flow diagram for a typical petroleum refinery.

TABLE 3-3. COMPARISON OF "REPRESENTATIVE" REFINERY PRODUCT SLATE WITH TOTAL ACTUAL U.S. PRODUCTION[13]

Product	Volume Percent of Total Refinery Products: Representative Refinery Production	Volume Percent of Total Refinery Products: Total U.S. Production (1974)
Gasoline	50.3	48.9
Kerosine	1.2	1.2
Jet Fuel,		
Naphtha type	1.5	1.5
Kerosine type	5.0	4.9
Distillate Fuel Oil	20.4	20.4
Asphalt	3.4	3.4
Residual Fuel Oil	8.2	8.2
Marketable Coke	1.4	1.4
LPG	2.4	2.4
Petrochemical Feedstocks	2.8	2.8
Other (Fuels, misc.)	3.4	4.9
TOTAL	100.0	100.0

TABLE 3-4. MAJOR REFINERY PROCESSES REQUIRING A FIRED HEATER

Process	Process Description	Heaters Used	Process Heat[a] Requirements KJ/liter	Process Heat[a] Requirements 10^3 Btu/bbl feed	Feedstock Temperature[a] Outlet of Heater °F
Distillation					
Atmospheric	Separates light hydrocarbons from crude in a distillation column under atmospheric conditions.	Preheater, Reboiler	590	89	700
Vacuum	Separates heavy gas oils from atmospheric distillation bottoms under vacuum.	Preheater, Reboiler	418	63	750 - 830
Thermal Processes					
Thermal Cracking	Thermal decomposition of large molecules into lighter, more valuable products.	Fired Reactor	4,648	700	850 - 1000
Coking	Cracking reactions allowed to go to completion. Lighter products and coke produced.	Preheater	1,525	230	900 - 975
Visebreaking	Mild cracking of residuals to improve their viscosity and produce lighter gas oils.	Fired Reactor	961	145	850 - 950
Catalytic Cracking					
Fluidized Catalytic Cracking	Cracking of heavy petroleum products. A catalyst is used to aid the reaction.	Preheater	663	100	600 - 885[b]
Catalytic Hydrocracking	Cracking heavy feedstocks to produce lighter products in the presence of hydrogen and a catalyst.	Preheater	1,293	195	400 - 850
Hydroprocessing					
Hydrodesulfurization	Remove contaminating metals, sulfur, and nitrogen from the feedstock, Hydrogen is added and reacted over a catalyst.	Preheater	431	65[c]	390 - 800
Hydrotreating	Less severe than hydrodesulfurization. Removes metals, nitrogen, and sulfur from lighter feedstocks. Hydrogen is added and reacted over a catalyst.	Preheater	497	75[d]	600 - 800
Hydroconversion					
Alkylation	Combination of two hydrocarbons to produce a higher molecular weight hydrocarbon. Heater used on the fractionator.	Reboiler	2,500	377[e]	400
Catalytic Reforming	Low octane napthas are converted to high octane, aromatic napthas. Feedstock is contacted with hydrogen over a catalyst.	Preheater	1,790	270	850 - 1000

[a] Based on data in references 16, 17.

[b] Based on data in references 17, 18.

[c] Heavy gas oils and middle distillates.

[d] Light distillate.

[e] Btu/barrel of total alkylate.

TABLE 3-5. 1973 ENERGY CONSUMPTION OF SEVERAL DIRECT-FIRED PROCESSES IN THE PETROLEUM REFINING INDUSTRY[19]

Process	Energy Consumption 10^{12} Btu/yr	Percent of Reported Total
Atmospheric Distillation	529	26.3
Catalytic reforming	407	20.2
Vacuum Distillation	297	14.8
Delayed Coking	266	13.2
Fluid Catalytic Cracking	229	11.4
Gas Oil Hydrotreating	120	6.0
Naphtha Hydrotreating	78	3.9
Alkylation	43	2.1
Thermal Cracking	23	1.2
Visbreaking	18	0.9
Reported Total	2,010	100.0

TABLE 3-6. CHARACTERISTICS OF THE EXISTING REFINERY FIRED HEATER POPULATION[20]

Heater Type	Mean Design Heat Release Rate MMBtu/hr	Estimated Heater Population
Natural Draft	69.4	3,020
Mechanical Draft, Ambient	103.6	180
Mechanical Draft, Preheat	135.4	42
All heaters	72.2	3,242

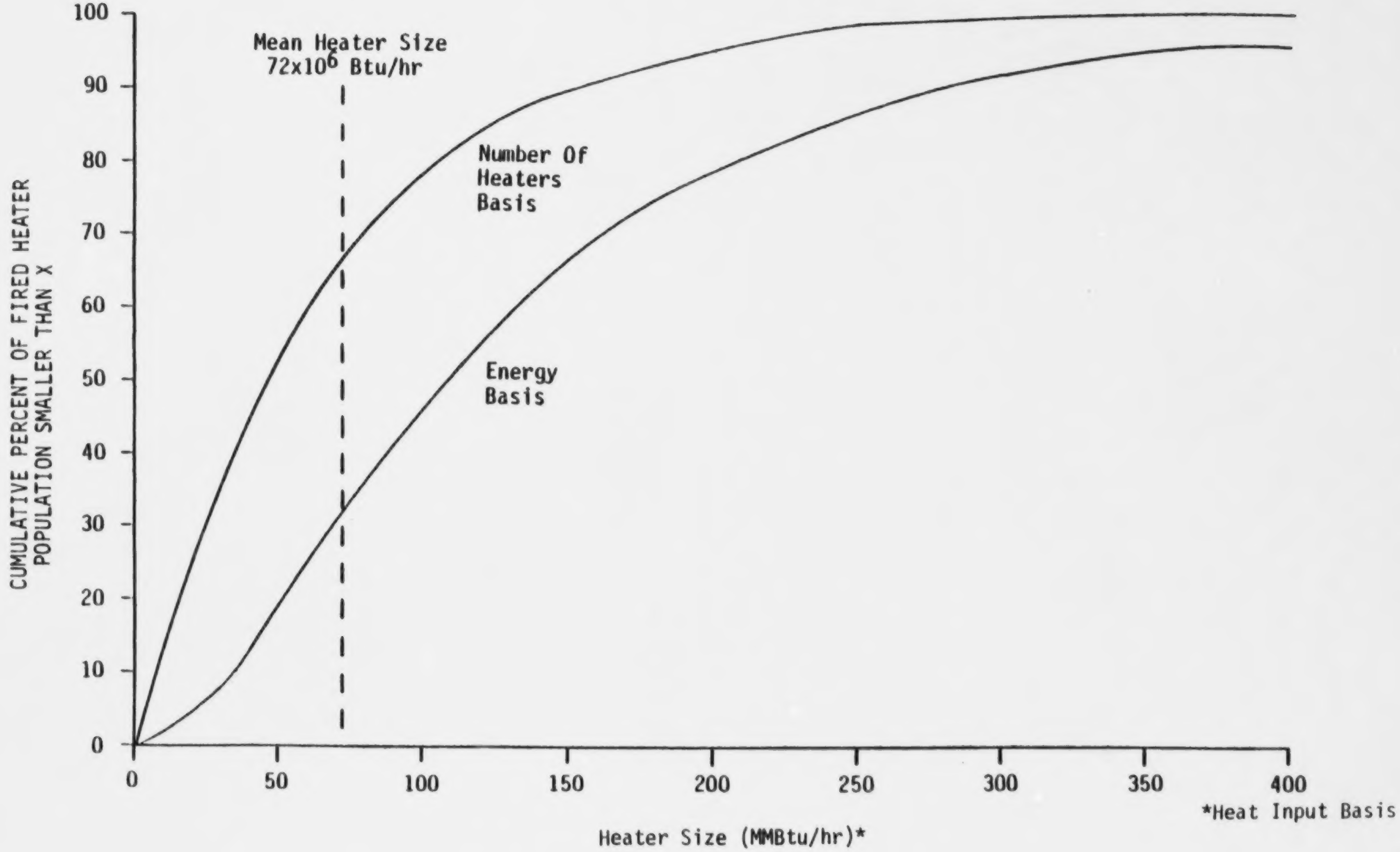

Figure 3-7. Size distribution of the existing fired heater population.[20]

3.1.4.2 Chemical Manufacturing Industry--

Fired heaters are used in a wide variety of applications in the chemical manufacturing industry (SIC 28). They are used as fired reactors (e.g., steam-hydrocarbon reformers and olefins pyrolysis furnaces), feed preheaters for non-fired reactors, reboilers for distillation operations, and heaters for heat transfer oils (e.g., Dowtherm heaters). More than 30 organic chemical and 7 inorganic chemical manufacturing operations are reported to require fired heaters, in addition to various miscellaneous uses in the chemical industry. Table 3-7 lists some of the specific applications of chemical industry heaters reported by the Chemical Manufacturers' Association (CMA).[21] The fired heater energy requirements of the major chemical manufacturing operations using fired heaters are shown in Table 3-8, along with the heater type(s) and firebox temperature, for each chemical. Although there are many other chemical manufacturing operations that use fired heaters (as shown in Table 3-7), the chemicals listed in Table 3-8 account for a large portion of the chemical industry fired heater use.

On the basis of process requirements, fired heater applications in the chemical industry can be broadly classified into two categories: (1) low and medium firebox temperature applications such as feed preheaters, reboilers, and steam superheaters and (2) high firebox temperature applications such as olefins pyrolysis furnaces and steam-hydrocarbon reformers. Low and medium firebox temperature chemical industry heaters are similar to those found in the petroleum refining industry. High firebox temperature heaters are unique to the chemical industry and are described below.

In pyrolysis, gaseous hydrocarbons such as ethane, propane, and butane, and heavier hydrocarbons such as naptha feedstocks are thermally converted to olefins such as ethylene and propylene. The basic criteria for pyrolysis furnaces are: adequate control of heat flux from inlet to outlet of the tubes, high heat transfer rates at high temperatures, short residence times, and uniform temperature distribution along the tube length. Several designs are available for pyrolysis furnaces. All are high firebox temperature designs, 1,900 to 2,300°F, and most employ the vertical box heater configuration. Table 3-9 summarizes the major features of several pyrolysis furnace designs.

TABLE 3-7. REPORTED APPLICATIONS OF FIRED HEATERS IN THE CHEMICAL MANUFACTURING INDUSTRY[21]

Category	Applications
Organic Chemicals Manufacturing	acetone, acetic anhydride, acetylene, acrylic acids, alkyl benzene, allyl chloride, amines, ammonia, benzene, benzoic acid and other aromatic acids, biphenyl, butadiene, chlorinated hydrocarbon solvents, cumene, cyclohexane, dimethyl terephthalate, diphenylamine, esters, ethanol and higher alcohols, ethylbenzene/styrene, ethylene/propylene, fatty acids, formaldehyde, ketone, maleic anhydride, methanol, methyl ethyl ketone, methylene dianiline, neo acids, phthalic anhydride, polyethylene, polyvinyl chloride, pyridine, salicylic acid, toluene diamine, toluene diisocyanate, xylene
Inorganic Chemicals Manufacturing	carbon bisulfite, carbon disulfide, carbon monoxide, caustic soda, hydrogen, silicones, sulfur chloride
Others	additives, agricultural products, asphalt, carbon black, elastomers, fabrics, finishes, pharmaceuticals, photo products, pigments, plasticizers, polyamide adhesives, synthetic fibers

TABLE 3-8. ENERGY REQUIREMENTS OF MAJOR FIRED HEATER APPLICATIONS IN THE CHEMICAL INDUSTRY

Chemical	Process	Heater type	Firebox Temperature (°F)	1985 Fired Heater Energy Requirement[19] 10^{12} Btu/yr	% of Known Chemical Industry Heater Requirements
Low and Medium Temperature Applications					
Benzene	Reformate extraction	Reboiler	700[22]	64.8	9.9
Styrene	Ethylbenzene dehydrogenation	Steam superheater	1,500 - 1,600[23]	32.1	4.9
Vinyl Chloride Monomer	Ethylene dichloride cracking	Cracking furnace	N/A	12.6	1.9
P-Xylene	Xylene isomerization	Reactor fired preheater	N/A	13.0	2.0
Dimethyl terephthalate	Reaction of p-xylene and methanol	Preheater, hot oil furnace	480 - 540[a,24]	11.1	1.7
Butadiene	Butylene dehydrogenation	Preheater, reboiler	1,100[25]	2.6	0.4
Ethanol(synthetic)	Ethylene hydration	Preheater	750[23]	1.3	0.2
Acetone	Various	Hot oil furnace	N/A	0.8	0.1
Others	See Table 3-7	-	-	N/A	
High Temperature Applications					
Ethylene/propylene	Thermal cracking	Pyrolysis furnace	1,900 - 2,300[26]	337.9	51.8
Ammonia	Natural gas reforming	Steam hydrocarbon reformer	1,500 - 1,600[27]	150.5	23.1
Methanol	Hydrocarbon reforming	Steam hydrocarbon	1,800 - 2000[27]	25.7	4.0
		TOTAL KNOWN FIRED HEATER ENERGY REQUIREMENT		652.4	100

[a] Feedstock outlet temperature.
N/A = data not available.

TABLE 3-9. SUMMARY OF MAJOR PYROLYSIS FURNACE DESIGN FEATURES

Furnace Designer	Heater Configuration	Burner Designer	Burner Manufacturer	Burner Type(s)	Use of Preheat
Foster Wheeler	(1) Multi cell box (smaller heaters)	John Zink National Air Oil	John Zink National Air Oil	Floor burners on multi cell heaters. Flat flame for both heaters. Raw gas or premix.	Yes
	(2) Terrace wall (larger heaters)	John Zink	John Zink	Floor burners, flat flame, duel fuel.	Yes
		National Air Oil	National Air Oil	Fuel fuel.	Yes
KTI	Vertical box	John Zink	John Zink	Radian wall, premix.	Yes
		National Air Oil	National Air Oil	Raw gas, duel fuel.	No
Kellogg	Vertical box	Kellogg	John Zink & Others	Radiant wall and flat flame floor-fired (both partial premix). Wall only, floor only, or wall and floor. Prefer always using floor burners.	Yes
		National Air Oil	National Air Oil	Floor burners, flat flame, dual fuel.	Yes
Lummus	Vertical box	Lummus	John Zink	Radian wall (100% premix) and flat flame floor-fired (partial premix). Wall only, floor only, or wall and floor.	Yes - Trend will be to use gas turbine exhaust with floor firing.
		National Air Oil	National Air Oil	Floor burners, flat flame, dual fuel.	Yes
Selas	Vertical box	Selas	Selas	Radian wall, premix. Have some wall and floor burners (10% of installations). Three types of burners for ethylene heaters. (1) High H_2 content fuel (2) Ethane/propane fuel (3) Use with preheat	Yes
Stone & Webster	Vertical box	John Zink	John Zink	Premix wall and floor. Both flat flame Floor burners can be premix or raw gas.	Yes

Steam-hydrocarbon reformers represent the other major application of high temperature fired heaters in the chemical manufacturing industry. The function of these furnaces is to reform natural gas or other hydrocarbons with steam to produce hydrogen and carbon monoxide. The reforming reactions are not favored by conditions below 1,100°F and proceed more favorably as the temperature increases. The firebox temperature of steam-hydrocarbon reformers ranges from about 1,800 to 2,000°F. The major features of several reformer furnace designs are shown in Table 3-10.

The 1985 energy demand of chemical industry fired heaters in major applications is estimated to be approximately 6.8 x 10^{14} Btu/yr. The details of these calculations are shown in Appendix A. Assuming an average chemical industry fired heater size of 56.1 MMBtu/hr as reported by the CMA,[21] this corresponds to an existing population of about 1400 chemical industry fired heaters. High firebox temperature heaters (i.e., olefins pyrolysis furnaces and steam hydrocarbon reformers) account for about 81 percent of the total chemical industry fired heater energy demand, or 5.5 x 10^{14} Btu/yr. Low and medium firebox temperature heaters account for about 19 percent of the total chemical industry fired heaters energy demand, or 1.3 x 10^{14} Btu/yr (see Appendix A).

3.1.5 Projected New Fired Heater Construction in the Petroleum Refining and Chemical Industries

Projections of fired heater construction in the petroleum refining and chemical industries depend on growth rates of the respective market sectors requiring fired heaters. This information will be discussed separately for each industry in Sections 3.1.5.1 and 3.1.5.2.

3.1.5.1 Projected New Fired Heater Construction in the Petroleum Refining Industry--

Estimates of fired heater growth in the petroleum refining industry were developed by analyzing data on new process unit construction in the industry in 1984. The annual production capacity growth rates for 1984 were

TABLE 3-10. SUMMARY OF MAJOR STEAM-HYDROCARBON REFORMER DESIGN FEATURES

Furnace Designer	Heater Configuration	Burner Designer	Burner Manufacturer	Burner Type(s)	Use of Preheat
Davy-McKee	Vertical Box	John Zink	John Zink	Down-fired, conical flame	Yes
		National Air Oil	National Air Oil	Down-fired, conical flame	Yes
Foster Wheeler	(1) Vertical Box	John Zink	John Zink	Down-fired, conical flame	Yes
		National Air Oil	National Air Oil	Down-fired, conical flame	Yes
	(2) Terrace wall	John Zink	John Zink	Flat flame	Yes
KTI	(1) Vertical box (large reformers)	John Zink	John Zink	Floor-fired, flat flame	Yes
	(2) Vertical Cylindrical (small reformers)	John Zink	John Zink	Floor-fired, flat flame	Yes
M.W. Kellogg	Vertical box	Kellogg	John Zink	Down-fired, flat flame	Yes
		National Air Oil	National Air Oil	Down-fired, flat flame	Yes
Lummus	Vertical box	Lummus	John Zink	Down-fired, flat flame	Yes
		National Air Oil	National Air Oil	Down-fired flat flame	Yes
Selas	Vertical box	Selas	Selas	(1) Down-fired, flat flame (new heaters)	Yes
				(2) Wall and floor-fired, flat flame (older heaters)	Yes

developed from reported refinery construction projects listed in Hydrocarbon Processing.[28] The process heat requirements (Btu/bbl) listed in Table 3-4 were then used to convert production capacity growth rates into fired heater energy demand growth rates. The results of the analysis are summarized below.

The growth in fired heaters energy demand in 1984 was estimated to be 14.6 x 10^{12} Btu. From 1985 to 1989, it is projected that the overall U.S. demand for petroleum products will not change significantly. Few, if any, new refineries are expected to be added during this period. However, as in 1984, additional downstream capacity will be built at existing refineries to accommodate heavier crude feedstocks and increasing demand for lighter finished products. It is assumed in this study that the annual growth in fired heater energy demand during the period 1985 to 1989 will be equal to the growth in 1984 (approximately 14.6 x 10^{12} Btu/year). The breakdown of refinery operations requiring process heaters over this period is shown in Table 3-11. This growth represents an annual downstream fired heater energy demand growth rate of 0.7 percent in 1986 relative to the estimated 1985 total refinery fired heater energy consumption of 2.2 x 10^{15} Btu/hr.[29] Based on the estimated energy demand, energy demand growth rate, and average refinery heater size, the following projections are made for new fired heaters construction during the period 1985 to 1989:

energy demand of new refinery heaters built between
1985 to 1989 = 73 x 10^{12} Btu/hr

number of new refinery heaters built between 1985 to
1989 = 80 heaters built by year end 1989 (16 heaters per year)

3.1.5.2 Projected New Fired Heater Construction in the Chemical Industry--

The demand for new fired heaters in the chemical industry depends on the current production growth rates and existing capacity utilizations of those sectors of the chemical industry that have fired heater applications. The current production levels, capacity utilizations, production growth

TABLE 3-11. PROJECTED NEW FIRED HEATER ENERGY CAPACITY ASSOCIATED WITH NEW PROCESS UNIT CONSTRUCTION IN THE PETROLEUM REFINERY INDUSTRY, 1985 - 1989

Category	Process Requiring Fired Heater(s)	Projected Annual Fired Heater Energy Growth of Category (Btu/yr) for 1985 to 1989
Cracking Operations	Fluidized Catalytic Cracking Catalytic Hydrocracking	8.7×10^{12}
Hydroprocessing	Hydrotreating, Hydrorefining: Hydrodesulfurization	2.0×10^{12}
Distillation	Crude Distillation, Vaccum Distillation	0
Conversion Processes	Catalytic Reforming, Platforming, Alkylation, Isomerization, Magnaforming, Hydrodealkylation	1.2×10^{12}
Thermal Operations	Delayed Coking, Fluid Coking, Visbreaking	2.7×10^{12}
Total		14.6×10^{12}

rates and fired heater energy requirements are shown in Table 3-12 for the major fired heater applications in the chemical industry. The overall annual chemical industry growth rate for fired heaters was estimated by calculating the individual annual fired heater energy growth rates of the chemicals shown in Table 3-12. Historically, a capacity utilization of 82 percent has triggered capacity expansion in the general manufacturing sector in the United States. Therefore, in this study it was assumed that, increased production demand will not trigger new construction until the utilization of nameplate capacity for a given chemical reached 82 percent. The details of the growth rate analysis are contained in Appendix A. Based on the data in Table 3-12, the annual chemical industry fired heater energy growth rate for the years 1985 to 1989 is approximately 2.2 percent relative to the projected 1985 fired heater energy demand of 1.3×10^{14} Btu/yr. Appoximately 81 percent of the estimated fired heater energy demand for 1985 is for high temperature applications and 19 percent in low and medium temperature capplicaiton.

The increase in new fired heater energy demand requiring new construction of fired heaters is projected at 73.5×10^{12} Btu/yr by year end 1989. Approximately 86 percent of this increase in fired heater energy demand is for high temperature applications and 12 percent in low and medium temperature applications. The data provided by the CMA[45] indicate that the average size of high temperatures heaters in the chemical industry is 350 MMBtu/hr, while low and medium temperature heaters in the chemical industry have an average size of 15 MMBtu/hr. Based on this, the following projections are made for new fired heater construction in the chemical industry for the years 1985 to 1989:

new fired heater energy demand requiring new construction by year end 1989:

low and medium temperature heaters:	10.5×10^{12} Btu/hr
high temperature heaters:	63.0×10^{12} Btu/hr
TOTAL	73.5×10^{12} Btu/hr

TABLE 3-12. PROJECTED PRODUCTION, UTILIZATION OF NAMEPLATE CAPACITY AND ANNUAL GROWTH FOR SELECTED CHEMICALS IN 1985

Chemical	Projected 1985 Production[30] (10^9 lbs)	Projected 1985[31] Utilization Of Namplate Capacity (%)	Projected 1986 Annual Production Growth Rate[a] (%)	Fired Heater Energy Requirement[b] (10^3 Btu/lb Feed)
Methanol	8.8	78	6.0	3.3
Ethylene	31.9	93	2.2	10.6
Ammonia	33.2	91	2.5	4.2
Benzene[c]	10.1	67	2.3	5.7
Styrene	8.1	100	5.0	4.2
Vinyl Chloride	7.9	72	4.5	1.6
Dimethyl Terepthalate	5.6	72	3.0	1.7
p-Xylene[d]	4.4	89	3.0	2.6
Acetone[e]	2.0	61	3.0	0.31
Butadiene	2.6	58	0.8	1.0
Ethanol	1.1	95	8.5	1.0

[a] Based on information presented in References 32 to 41.

[b] Based on information presented in References 42, 43, 44.

[c] Benzene is a coproduct with xylene and ethylbenzene.

[d] p-Xylene is a coproduct with o-xylene.

[e] Acetone is a coproduct with phenol.

number of new heaters constructed (based on average heater sizes) by year end 1989:

low and medium temperature heaters:	83
high temperature heaters:	21
TOTAL	104

For both the chemical and refining industries, the following projections are made for the years 1985 to 1989.

projected total number of new heaters constructed between 1985 and 1989:

Chemical Industry	104
Refining Industry	80
TOTAL	184

3.2 NO_x EMISSIONS FROM FIRED HEATERS

3.2.1 NO_x Formation Mechanisms

Oxides of nitrogen, NO_x (NO and NO_2), are formed in fired heaters by two mechanisms: thermal NO_x formation and fuel NO_x formation. Thermal NO_x is the result of the reaction between atmospheric nitrogen and oxygen, while fuel NO_x is the result of the reaction between fuel-bound nitrogen and oxygen. The relative contributions of the two mechanisms to total NO_x emissions depend on heater operating conditions and fuel characteristics. NO_x emissions from natural gas and refinery gas-fired heaters are due to thermal NO_x formation since these fuels usually do not contain chemically bound nitrogen. However, some refinery gases may have trace amounts of HCN, NH_3 or other nitrogen bearing species which may be oxidized to NO_x. NO_x emissions from oil-fired heaters are due to both thermal and fuel NO_x formation. The factors affecting NO_x formation by each of the two mechanisms are briefly discussed below.

3.2.1.1 Thermal NO_x--

Nitrogen oxides are formed during combustion by the high temperature thermal fixation of atmospheric nitrogen, which becomes significant at temperatures exceeding about 1810 K (2800°F). Nitric oxide (NO) is the predominant species of NO_x formed. Kinetic considerations based on the Zeldovich mechanism suggest that thermal NO_x formation can be described by the following simplified expression:

$$[NO] = k_1 \, e^{-k_2/T} \, [N_2] \, [O_2]^{0.5} \, t$$

where [ ] = mole fraction
T = peak flame temperature (K)
t = residence time of reactants at peak flame temperature
k_1, k_2 = constants

Although the above expression does not account for the effects of fuel/air mixing or the possible interaction of hydrocarbon radicals with thermal NO_x formation, it does identify the key parameters that affect thermal NO_x formation: temperature, oxygen and nitrogen concentrations, and residence time in the flame zone.

While it is difficult to verify quantitatively the predicted effects of local oxygen concentration and peak flame temperature on NO_x emissions, these effects can be demonstrated by investigating the dependence of NO_x formation on the surrogate variables flue gas oxygen and degree of combustion air preheat. The local oxygen concentration in the flame zone is directly related to flue gas oxygen, and the peak flame temperature increases with an increase in the degree of combustion air preheat. Figure 3-8 shows the relationship between NO_x emissions and flue gas oxygen at various elevated combustion air preheat temperatures for a natural gas-fired test furnace. The data suggest a synergistic influence of excess air and degree of combustion air preheat on NO_x emissions. Variation in the

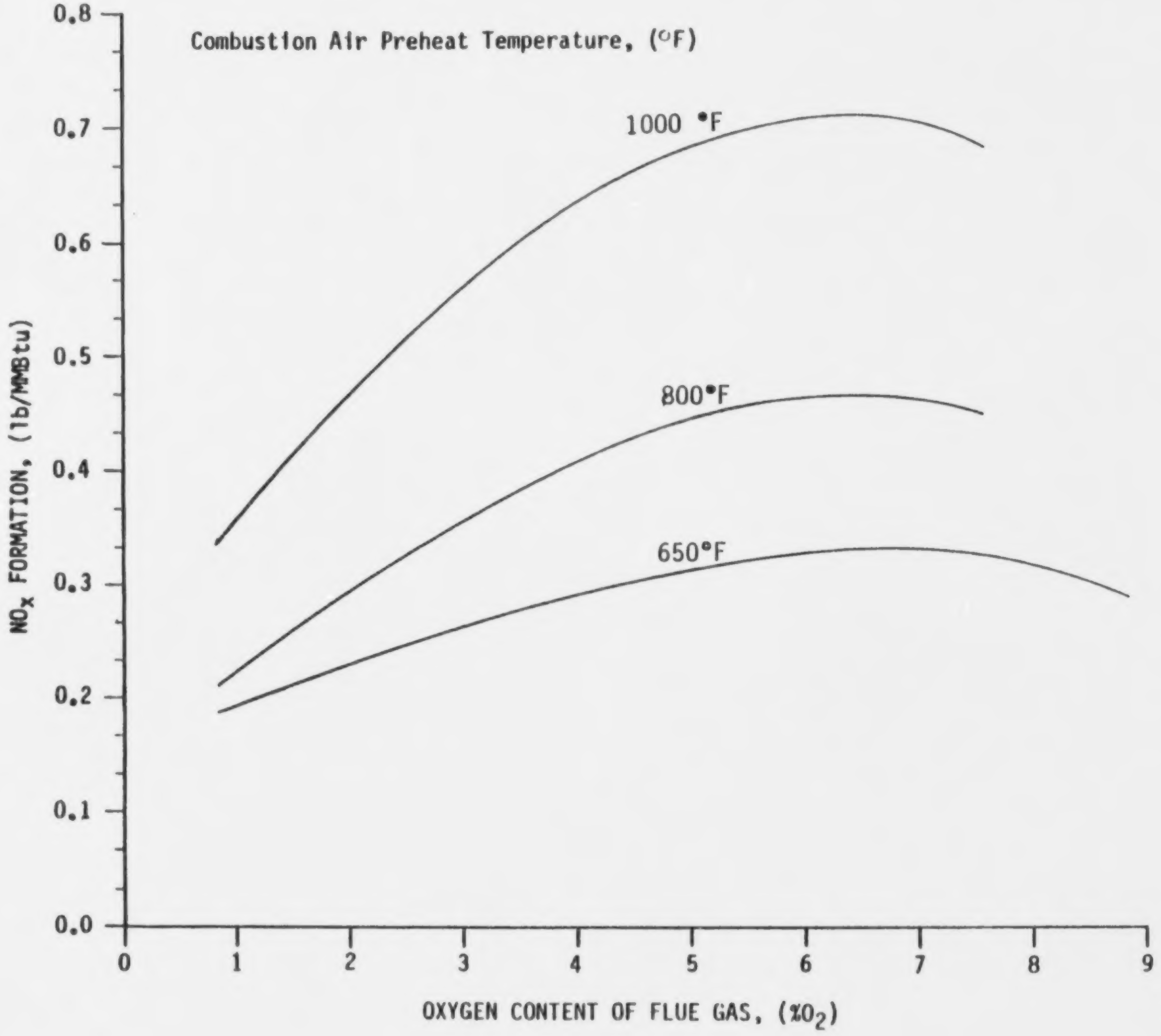

Figure 3-8. Effect of excess air on gas-fired NO_x formation at various combustion air preheat temperatures. Adapted from reference 46.

flue gas oxygen level from 1 percent to 6 percent resulted in a NO_x emissions increase by a factor of about 1.5 at a combustion air preheat temperature of 650°F, and by a factor of about 2.3 at a combustion air preheat temperature of 1,200°F. Thus, the effect of excess air on NO_x emissions becomes more pronounced as the degree of combustion air preheat is increased. The data also show that large amounts of excess air (above 6 percent O_2 in Figure 3-8) can result in reduced levels of NO_x emissions. This phenomenon may be explained by the flame cooling effect of increased excess air in conjunction with the temperature sensitivity of the thermal NO_x formation mechanism.

The effects of the combustion air preheat temperature on NO_x emissions from a test furnace operated by a major burner vendor for both a conventional raw gas burner and a standard oil-fired burner at a fixed excess air level are shown in Figure 3-9. The data indicate that for both fuel types, preheating the combustion air to 400°F increases NO_x emissions by a factor of about 1.4 relative to the NO_x emissions with ambient temperature combustion air.

3.2.1.2 Fuel NO_x--

The mechanisms by which chemically bound fuel nitrogen compounds are converted to NO_x emissions are not fully understood. It is theorized that the rate of fuel NO_x formation is dependent on the degree of fuel/air mixing, the fuel nitrogen concentration, and the local oxygen concentration in the combustion zone. Fuel NO_x formation is considered to be fairly insensitive to temperature and can occur at much lower temperatures than thermal NO_x formation. The available data indicate that the conversion of fuel bound nitrogen to NO_x emissions ranges from 15 to 100 percent, and decreases with increasing fuel nitrogen content. Figure 3-10 shows the effect of fuel nitrogen content on NO_x emissions from a high intensity oil burner operated at fixed excess air and a fixed combustion air temperature of 90°F. The overall contribution of fuel NO_x to the total NO_x formation in 100% oil-fired heaters is not well-documented. However, it is expected that fuel NO_x formation represents a significant fraction of the total NO_x when high-nitrogen fuels such as residual oil are combusted. Regression models

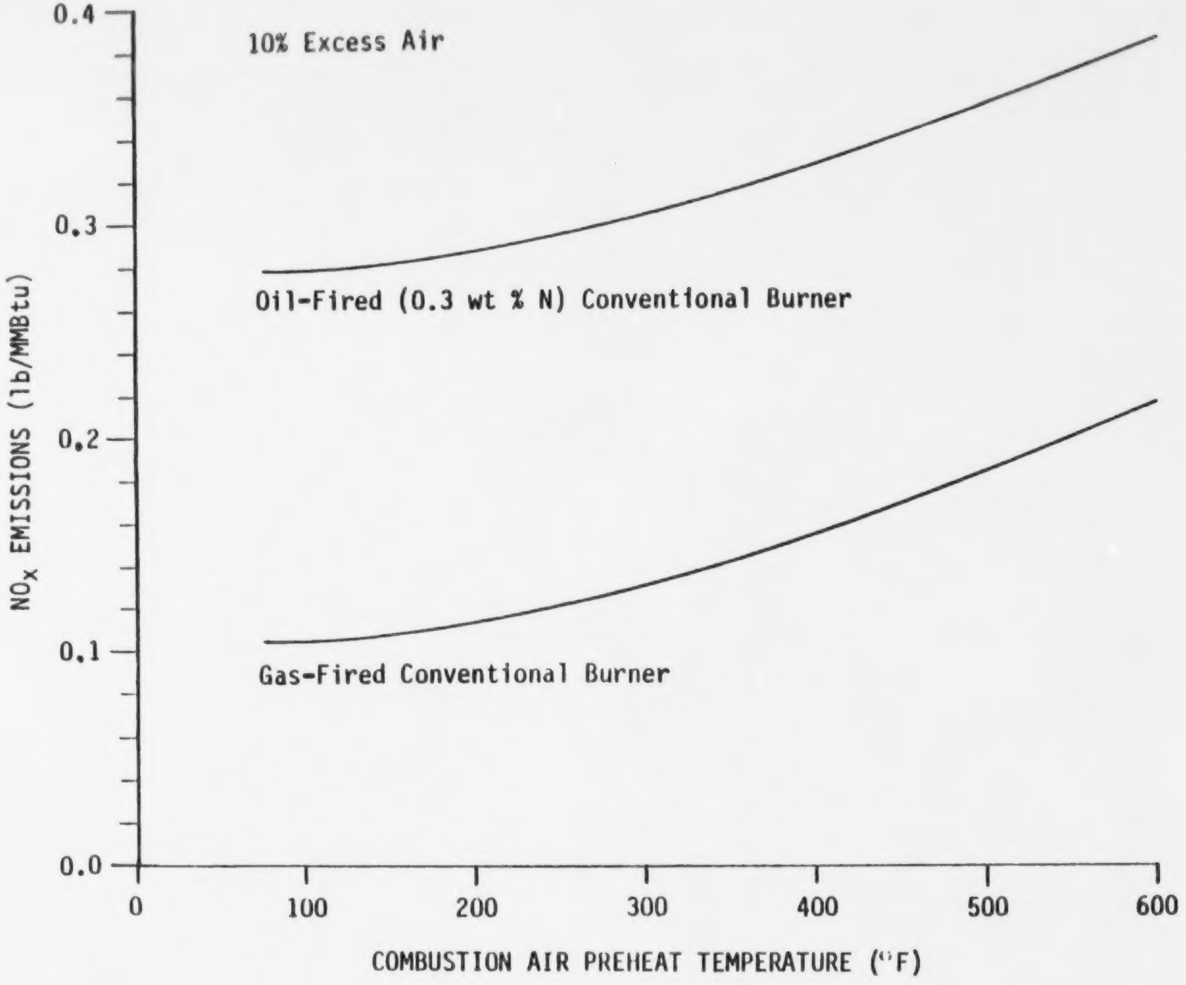

Figure 3-9. Effect of combustion air preheat temperature on NO_x emissions. Adapted from reference 47.

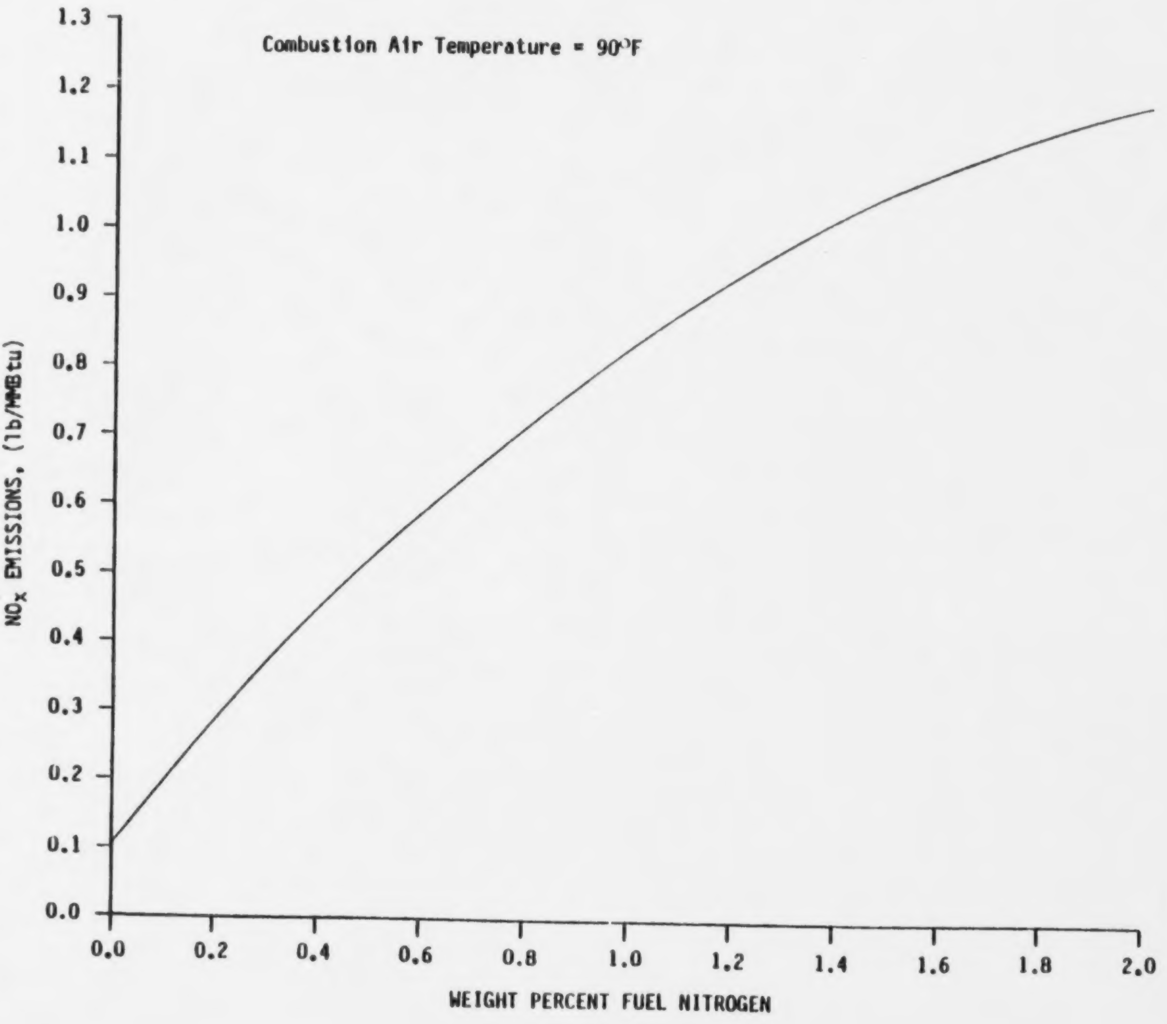

Figure 3-10. Effect of fuel nitrogen content on NO$_x$ emissions for a Zink-Phillips high intensity burner. Adapted from reference 49.

developed to predict NO_x emissions from 100% oil-fired industrial boilers indicate a nearly proportional relationship between NO_x emissions and fuel nitrogen content for conventional fuel oil burners.[48] Furthermore, these regression models show that the NO_x emissions from a watertube oil-fired boiler operated at fixed excess air conditions can increase by as much as a factor of 6 as the fuel nitrogen content is increased from 0 to 1.0 weight percent.

3.2.2 Heater Design Parameters Affecting NO_x Emissions

NO_x emissions from fired heaters depend on several heater design parameters. The most significant of these are identified and discussed below.

3.2.2.1 Fuel Type--

The most important design parameter affecting NO_x emissions from a fired heater is the type of fuel (i.e., the nitrogen content of the fuel) that the heater is designed to fire. Oil-fired heaters can be expected to generate higher NO_x emissions per unit of energy input than comparable gas-fired heaters. Regression models developed to correlate NO_x emissions data from industrial boilers indicate that NO_x emissions from low-nitrogen distillate oil-fired boilers are about 1.3 times higher than those from boilers firing natural gas at identical conditions of heat release rate, excess air, and combustion air preheat.[50] As discussed in Section 3.2.1.2, differences in fuel nitrogen content corresponding to typical distillate and residual oils can result in as much as an additional 6-fold increase in NO_x emissions. Thus, the results of the industrial boiler NO_x emission regression modelling demonstrate that fuel type has a large effect on the magnitude of NO_x emissions from a combustion source. On a qualitative basis these conclusions are valid regardless of whether the combustion source is an industrial boiler or a fired heater.

3.2.2.2 Burner Type--

Another design factor having a large effect on NO_x emissions from fired heaters is burner type. Most burners selected for new fired heater installations will be capable of firing only oil, only gas, or oil and gas simultaneously. The NO_x emissions characteristics of these combination burners can best be discussed by considering their gas and oil-firing components individually.

Oil-fired burners differ primarily in the methods used to atomize the oil prior to combustion. Steam atomization is used almost exclusively in fired heaters. Although the atomized oil drop size has been theorized to influence NO_x emissions, a definite relation between drop size and NO_x formation has not been determined. Steam atomized oil burners can be divided into two categories: conventional oil burners and staged combustion air oil burners. Conventional oil burners have a single combustion zone in which all of the air is fed to the atomized fuel oil. Staged combustion air oil burners make use of at least two separate air injection sections. Decreased NO_x emissions are achieved with these burners by operating a primary air/fuel injection section at substoichiometric combustion air conditions and injecting secondary air downstream of the primary section to complete combustion. NO_x formation in the primary air/fuel injection section is limited by the reducing conditions associated with substoichiometric combustion. Data from independent tests on an actual fired heater installation are not available to compare the NO_x emissions of staged combustion air oil-fired burners versus conventional oil-fired burners installed on the same heater. Test-scale oil-fired staged combustion air burners have been shown to be capable of achieving NO_x emissions reductions as large as a factor of 2 or 3 relative to unstaged burners when the fraction of combustion air introduced in the primary combustion zone is optimized. Thus, burner design is a very significant factor affecting NO_x emissions from oil-fired heaters.

As discussed in Section 3.1.2.4, several gas burner designs are available. The NO_x emissions characteristics of each type have been demonstrated by tests conducted on several fired heaters. Burner vendor data indicate that NO_x emissions from a heater with low-NO_x burners are approximately 30 percent lower than NO_x emission from the same heater with conventional raw gas burners. These data are discussed in more detail in Section 4. There are no data available that substantiate differences in emissions between heaters with premix burners and conventional raw gas burners.

3.2.2.3 Use of Combustion Air Preheat--

As discussed in Section 3.2.1.1, the use of combustion air preheat causes an increase in the amount of NO_x formed in the heater by virtue of increased flame temperature. Increasing the degree of preheat will also cause an increase in NO_x emissions. Figure 3-9 of Section 3.2.1.1 shows that NO_x emissions for a test-scale mechanical draft heater increased by a factor of about 1.4 when the temperature of the combustion air was raised from ambient 70°F to 400°F. A study done by a major U.S. refining company on the effects of combustion air preheat on NO_x emissions concluded that for combustion air temperatures of 300 to 640°F, combustion air preheat increased NO_x emissions by a factor of 1.3 to 1.7 relative to ambient temperature combustion air.[51]

3.2.2.4 Firebox Temperature--

The firebox temperature required for a given fired heater application is expected to influence NO_x emissions because of the relation between firebox temperature and flame temperature. High firebox temperature heater applications such as steam-hydrocarbon reformers and olefins pyrolysis furnaces are likely to have higher NO_x emissions than the low and medium temperature fired heater applications. Data from a major burner manufacturer shown in Figure 3-11 indicate that when all other factors are held constant, thermal NO_x emissions from gas-fired heaters increase by a factor of about 1.5 when the firebox temperature is increased from 1,300°F to 1,900°F.[49] The effect of firebox temperature on fuel NO_x emissions from oil fired heaters has not been reported. However, fuel NO_x is less sensitive to temperature than thermal NO_x.

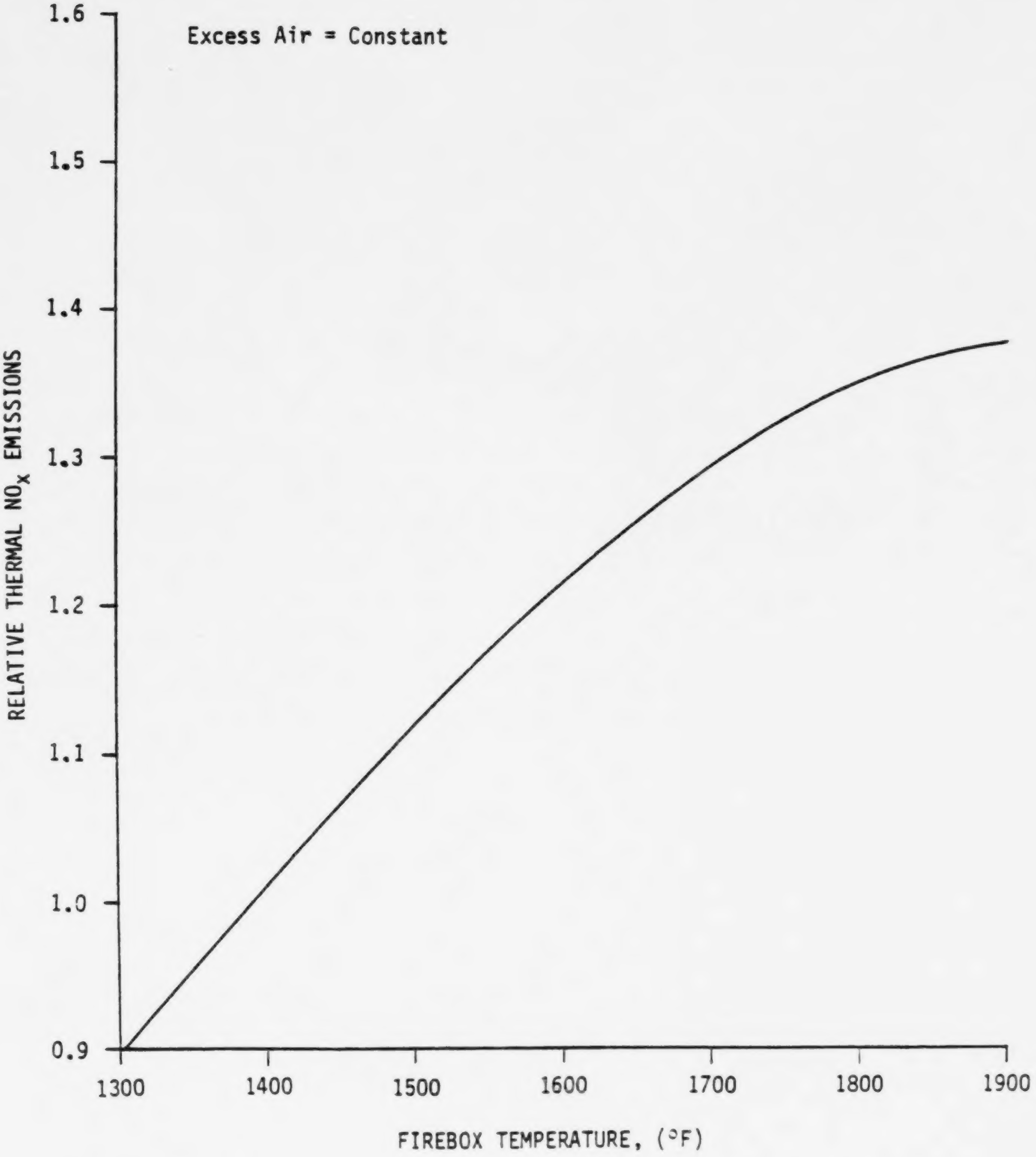

Figure 3-11. Effect of firebox temperature on thermal NO_x formation.[49]

*Reproduced with permission from John Zink Services, Inc.

3.2.2.5 Draft Type--

Draft type might be expected to affect NO_x emissions from fired heaters due to differences in the degree of fuel/air mixing between natural and mechanical draft air supply systems. For a given excess oxygen level and ambient combustion air supply, mechanical draft heaters might be expected to yield higher concentrations of NO_x than natural draft heaters due to enhanced air/fuel mixing in the combustion zone and increased combustion intensity. However, since mechanical draft heaters can be operated at lower excess air levels and higher thermal efficiencies than natural draft heaters, the NO_x emission factor per unit of energy input under actual operating conditions could be lower for mechanical draft heaters than for natural draft heaters.

3.2.2.6 Miscellaneous Design Parameters

Several miscellaneous heater design parameters may also affect NO_x emissions from fired heaters. Included in this group are firebox and tube orientation, the number and spacing of burners, and the burner locations. One heater manufacturer has stated that floor-fired burners have higher NO_x emissions than wall-fired burners when all other heater parameters are identical.[52] However, insufficient data are available for any of the above variables to quantitatively assess their effects on NO_x emissions from fired heaters.

3.2.3 Heater Operating Parameters Affecting NO_x Emissions

In addition to the design parameters discussed in Section 3.2.2, several operating parameters can have significant effects on the level of NO_x produced by a fired heater. The most significant of these are identified and discussed below.

3.2.3.1 Excess Air--

It is well demonstrated that an increase in the excess air level of a fired heater under typical operating conditions results in an increase in

NO_x emissions. Long-term continuous NO_x emissions data were obtained in this study for 12 fired heaters in three petroleum refineries. These data included from about 540 to 3,400 hourly data points for each heater. The hourly measurements included NO_x emission rates, stack oxygen levels, and heater firing rates for all heaters. Additionally, for some of the heaters fuel gas H_2 content and the relative amounts of gas and oil fired were also measured. These data were analyzed statistically to quantify the effect of excess air on NO_x emissions. The NO_x data were correlated using the following functional form:

$$E = C_1 L^{C_2} A^{C_3} (1 + R)^{C_4} (1 + H)^{C_5}$$

where: E = NO_x emissions, [lb/10^6 Btu]

L = fractional load (operating heat release rate ÷ design heat release rate

A = stack oxygen (volume fraction of O_2)

R = oil fraction ratio of oil-fired Btu to total fuel fired oil and gas Btu

H = fuel gas H_2 content (volume fraction)

C_1, C_2, C_3, C_4, C_5 = regression model constants

The regression-based results shown in Table 3-13 show that NO_x emissions typically increase about 9 percent for each 1 percent increase in the measured stack oxygen level. Descriptions of the heaters represented in Table 3-13 and additional details concerning the statistical analysis are contained in Section 4.1.3.

Fired heaters are operated over a wide range of stack oxygen levels, depending largely on operator preference. Some excess air is required to insure complete combustion, but usually fired heaters are operated well above this minimum required excess air level. The minimum stack oxygen level achievable for a given heater is a function of fuel type, draft type, and the presence or absence of air leaks, burner design, rate of fuel/air mixing, the method of distributing air to the burners in multiple burner

TABLE 3-13. PERCENT REDUCTION OF NO$_x$ EMISSIONS PER PERCENT DECREASE IN STACK OXYGEN LEVEL FOR TWELVE HEATERS IN THE LONG TERM DATA BASE

Draft Type	Heater Code	$\Delta NO_x/\Delta O_2 \times 100\%$[a]
Natural Draft	A	10.1
	B	7.2
	C	13.8
	D	6.5
	E	12.0
	F	16.4
	G	8.2
	H	4.7
	K	6.9
	L	6.7
	I	4.4
	Average	8.9
Mechanical Draft	J	10.5
	Average	10.5
Overall Average (natural draft and mechanical draft)		9.0

$$^{a}\frac{\Delta NO_x}{\Delta O_2} = \frac{\left[[NO_x]_{baseline} - [NO_x]_y\right]}{[NO_x]_{baseline}} \Big/ SOL_{baseline} - SOL_y$$

where SOL = Stack Oxygen Level
baseline = 5.5% O_2
y = 3% O_2 for natural draft heaters;
2% O_2 for mechanical draft heaters.
$[NO_x]$ = NO_x emission factor (lb/MMBtu)

furnaces. No quantitative data are available on the minimum stack oxygen level achievable in oil versus gas-fired heaters, but minimum oxygen levels are expected to be higher for oil firing than for gas firing because of the inherent problems associated with combustion air/fuel oil mixing. Because mechanical draft heaters allow more precise control of combustion air supply, they can be operated at lower stack oxygen levels than natural draft heaters. Similarly, the minimum possible long term average excess air levels that can be achieved by new gas-fired heaters is expected to be lower than that demonstrated for existing heaters because of the absence of air leaks in new heaters.

Information was obtained in this study on the stack oxygen levels of 178 fired heaters. These data indicated that the average stack oxygen level for these heaters was about 5.5 percent. No differences in oxygen levels were found due to draft or fuel type. Table 3-14 presents a summary of these data.

3.2.3.2 Degree of Combustion Air Preheat--

The degree of combustion air preheat employed in a fired heater equipped with a combustion air preheat system can have a large effect on NO_x emissions. Based on the test furnace data shown in Figure 3-9, NO_x emissions increase with increasing combustion air temperature. NO_x emissions from a fired heater with a combustion air preheat temperature of 400°F are about 1.4 times higher than they would be from the same heater with ambient combustion air. If the combustion air temperature were increased further to 600°F, the NO_x emissions would be about 2.1 times higher than they would be with ambient combustion air.

3.2.3.3 Oil/Gas Ratio for Combined Fired Heaters--

The relative proportions of oil and gas fired in a combined fired heater will affect NO_x emissions. It is expected that NO_x emissions from combined fired heaters increase with an increase in the relative amount of oil firing because NO_x emissions from 100% oil fired heaters are greater than NO_x emission from 100% gas fired heaters. However, sufficient NO_x

TABLE 3-14. SUMMARY OF NO_x EMISSIONS TEST DATA FOR FIRED HEATERS

Heater/Burner Type[a]	Number of Heaters Tested	Short Term Emissions Data Base Operating Oyxgen Level, % O_2 Average (Range)[b]	NO_x Emissions lb/MMBtu Average (Range)[b]	Number of Heaters Tested	Long Term Emissions Data Base Operating Oxygen Level, % O_2 Average (Range)[b]	NO_x Emissions lb/MMBtu Average (Range)	Data Source(s)
G-LNB-MD-PH	7	4.1 (2.0 - 5.7)	0.13 (0.07 - 0.16)	0	-	-	53, 54
G-RGB-MD-PH	8	4.3 (2.0 - 6.3)	0.32 (0.03 - 1.01)	1	7.4 (0.6 - 17.8)	0.20 (0.05 - 0.37)	53, 55, 56
G-PMB-MD-PH	0	-	-	0	-	-	-
G-SAB-MD-AMB	2	4.6 (3.8 - 5.3)	0.09 (0.08 - 0.09)	0	-	-	52
G-SAB-MD-AMB	2	8.1 (8.0 - 8.2)	0.06 (0.04 - 0.08)	0	-	-	52
G-SAB-ND	3	4.6 (3.5 - 5.8)	0.09 (0.05 - 0.11)	3	5.6 (4.4 - 6.4)	0.11 (0.10 - 0.13)	57, 59
G-RGB-ND	33	6.3 (2.9 - 14.6)[c]	0.13 (0.05 - 0.20)[c]	2	6.9 (5.1 - 8.8)	0.11 (0.10 - 0.11)	53, 55, 64
G-PMB-ND	1	7.3 (7.3 - 7.3)	0.12 (0.12 - 0.12)	3	5.0 (2.9 - 8.5)	0.11 (0.10 - 0.13)	53, 58
O-SAB-MD/PH	0	-	-	0	-	-	-
O-COB-MD/PH	0	-	-	0	-	-	-
O-SAB-MD/AMB	0	-	-	0	-	-	-
O-COB-MD/AMB	0	-	-	0	-	-	-
O-SAB-ND	5	6.7 (4.9 - 9.0)	0.37 (0.19 - 0.63)	0	-	-	52, 59
O-COB-ND	6	6.8 (4.5 - 9.9)	0.36 (0.18 - 0.51)	0	-	-	52, 59, 61
G/O-SAB-ND	0	-	-	2	3.9 (3.8 - 3.9)	0.11 (0.09 - 0.13)	57
G/O-RGB-ND	2	4.1 (4.0 - 4.2)	0.24 (0.24 - 0.24)	0	-	-	62
O/G-SAB-ND	2	7.6 (7.4 - 7.7)	0.41 (0.36 - 0.46)	0	-	-	54
O/G-COB-ND	7	5.4 (2.4 - 11.0)	0.29 (0.19 - 0.41)	0	-	-	62, 64, 65
G-ND	43	5.2	d	-	-	-	66, 67
O/G-ND	26	5.3	d	-	-	-	66, 67
O/G-MD/PH	2	6.6	d	-	-	-	66
TOTAL	178	5.5 Average (Both short term and long term data)					

---

[a] G = gas-fired; O = oil-fired; RGB = conventional raw gas burner; SAB = staged-air burners; PMB = premix burner; COB = conventional oil burner; ND = natural draft; MD = mechanical draft; AMB = ambient combustion air; PH = combustion air preheat.

[b] This is the range of the mean values for individual heaters in the category.

[c] The spot test G-RGB-ND category includes some data from heaters whose burner type is unknown but is assumed to be conventional raw gas.

[d] Corresponding NO_x data were not available.

emissions test data are not currently available to assess quantitatively the NO_x emissions behavior of combined fired heaters operated over a wide range of oil:gas ratios. NO_x emissions from the heaters in the long term data base collected in this study are shown in Table 3-15 for typical and low excess air stack oxygen levels. Average NO_x emissions from heaters K and L, which are oil/gas combined fired, cannot be clearly distinguished from the NO_x emissions from the other natural draft heaters (Heaters A-H). Heater K operated at approximately 27 percent oil firing (energy basis) while heater L operated at about 9 percent oil firing (energy basis). Data are not available on any one heater for which NO_x emissions were measured over a wide range of oil to gas ratios.

3.2.3.4 Fuel Composition and Heating Value--

Fluctuations in fuel composition and heating value may affect NO_x emissions from fired heaters. When refinery gas is fired, variations in hydrogen content can cause transient changes in the combustion characteristics of the fuel. A study conducted at one major refinery[68] found that the fuel gas hydrogen content varied from 0 to 50 percent, resulting in heating values ranging from 700 to 2,200 Btu/scf. The largest change in fuel gas content over a 24 hour period corresponded to about a 45 percent change in heating value. These transient variations in fuel combustion characteristics give rise to changes in flame temperature, flame speed, and flame volume. In particular the increased flame temperature of high-hydrogen refinery gas would be expected to result in increased NO_x emissions. Data presented in the same study indicated that a hydrogen:propane mixture with a heating value similar to that of natural gas had 50 percent higher NO_x emissions than pure propane when fired in a test furnace. The measured NO_x emissions increase due to addition of hydrogen to a natural gas-fired mechanical draft heater with combustion air preheat was approximately 24 percent. The study concluded that NO_x emissions from similar heaters combusting gaseous fuels with various concentrations of hydrogen at the subject refinery were not significantly different. Thus, although the hydrogen content of refinery gas seems to have an effect on NO_x emissions under test conditions, the effect is not well documented on actual heater installations.

TABLE 3-15. COMPARISON OF NO_x EMISSION LEVELS FOR HEATERS IN THE LONG TERM NO_x EMISSIONS DATA BASE

Heater Classification[a]	Heater Code	Stack Oxygen Level Baseline[b]	 Low Excess Air[c]
G-RGB-ND	A	0.113	0.085
	B	0.009	0.073
Classification Average		0.101	0.079
G-SAB-ND	F	0.105	0.077
	G	0.137	0.109
	H	0.112	0.100
	I	0.123	0.111
Classification Average		0.119	0.099
G-PMB-ND	C	0.147	0.094
	D	0.129	0.108
	E	0.103	0.073
Classification Average		0.126	0.092
O/G-SAB-ND	K	0.144	0.119
	L	0.087	0.072
Classification Average		0.116	0.096
G-RGB-MD/PH	J	0.198	0.125
Classification Average		0.198	0.125

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[a] For explanation of notation, see Table 3-14.

[b] Baseline = 5.5% O_2

[c] Low Excess Air = 3% O_2 for natural draft heaters;
2% O_2 for mechanical draft heaters.

Increases in fuel nitrogen content will increase NO_x emissions from oil-fired heaters. Unlike the case of refinery gas-fired heaters, however, variations in NO_x emissions from oil-fired heaters caused by changes in fuel composition are not expected to be transient in nature.

3.2.3.5 Heater Load--

The fractional use of heater capacity may affect NO_x emissions by altering firebox temperature. A heater operated at or near full load has a higher firebox temperature than when it is operated at low load. As discussed earlier in Section 3.2.2.5, high firebox temperatures are expected to lead to increased NO_x emissions from the heater due to increased flame temperature.

3.2.3.6 Burner Adjustments--

Burner adjustments can affect NO_x emissions by altering the flame characteristics. For example, burner adjustments that increase flame length also reduce peak flame temperature, thereby reducing NO_x emissions. For heaters equipped with staged air burners, the relative amounts of air introduced in the primary and secondary burner combustion zones can have large effects on NO_x emissions. Staged combustion burner test data on pilot units indicate that an optimum distribution of air between the two burner zones minimizes the formation of NO_x at a given overall excess air level.[69] Although adjustment of the combustion air distribution between the primary and secondary air registers is not used as a practical response to minor fluctuations in heater performance, the combustion air distribution can be adjusted to minimize NO_x emissions from the heater.

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SECTION 4

NO_x EMISSIONS CONTROL TECHNIQUES FOR FIRED HEATERS

This section presents NO_x emission control techniques that have been used on fired heaters in commercial applications. The control techniques are categorized as either combustion modifications or flue gas treatment. The most prevalent of the combustion modifications in commercial applications are low excess air controls (LEA), and low-NO_x burners. LEA and low-NO_x burners are discussed in Sections 4.1 and 4.2, respectively. The other combustion modifications considered in this section are staged combustion air lances (SCA) and flue gas recirculation (FGR) which are discussed in Sections 4.3 and 4.4, respectively. Flue gas NO_x treatment techniques are covered in less detail than combustion modifications because they are not as cost effective for fired heater applications. The flue gas treatment techniques discussed are selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR), which are discussed in Section 4.5. Table 4-1 gives a qualitative indication of the prevalence and/or developmental status of each of the control techniques.

4.1 LOW EXCESS AIR (LEA)

The following sections describe low excess air technology (Section 4.1.1), applicability to fired heaters (Section 4.1.2) and NO_x emissions performance data (Section 4.1.3).

4.1.1 Technology Description

Low excess air (LEA) control systems optimize the amount of air available for combustion. Optimization of the combustion air supply reduces fuel consumption and NO_x formation. Decreased local oxygen concentrations

TABLE 4-1. MAJOR NO_x EMISSION CONTROL TECHNOLOGIES FOR FIRED HEATERS

Control Technique	Current Use	Projected Use
1. Low Excess Air Controls	1. More than 50 fired heaters use automatic low excess air controls.	1. Expected to be applied to mainly large heaters and high temperature heaters.
2. Low-NO_x Burners	2. About 10% of all existing burner installations are low-NO_x burners.	2. About 50% of all new burner installations expected to be low NO_x burners.
3. Staged Air Addition (Air Lances)	3. Three low-temperature heaters have been retrofitted with air lances.	3. Not expected to be extensively applied to new heaters in the next five years.
4. Flue Gas Recirculation	4. No full scale applications shown.	4. Not expected to be extensively applied.
1. Selective Catalytic Reduction	1. Has been applied to at least nine heaters in California.	1. May find some use in NO_x non-attainment areas.
2. Selective Non-Catalytic Reduction	2. Has been applied to several heaters.	2. May find some use in NO_x non-attainment areas.

due to minimal excess air in the combustion zone form a reducing atmosphere which inhibits the formation of thermal and fuel NO_x. Additionally, the resulting lower flue gas temperature reduces the formation of thermal NO_x. Fuel consumption is reduced by minimizing heat loss due to the heating of excess air not required for stoichiometric combustion. More heat is transferred to the process fluid per unit of energy input, thus requiring less fuel to provide the required heat flux.[1] Typically for a one percent reduction in the stack oxygen level, the heater efficiency can be expected to improve approximately 0.5 percent.[2] The actual efficiency improvement obtained for a given heater depends on the flue gas temperature and on the heat transfer response of the heater to the reduced flue gas flow under LEA conditions.

The effectiveness of any LEA control system in reducing NO_x emissions from a fired heater depends on (i) the long-term average excess air level that can be maintained in the heater and (ii) the relationship between NO_x and O_2 in the heater. The lowest excess air level that can be maintained in a fired heater will depend on draft type, fuel type, degree of air inleakage into the heater and the ability of the excess air control system to respond quickly to changes in fuel composition and heater load. The relationship between NO_x emissions and O_2 for a particular heater will depend on draft type, fuel type, burner type, and degree of combustion air preheat as discussed in Section 3.2.

Draft type influences the excess air level attainable in a heater by affecting the degree of fuel/air mixing in the burner. Mechanical draft burners generally operate under a higher pressure drop than natural draft burners, resulting in improved fuel/air mixing. Consequently, mechanical draft heaters can achieve complete combustion at lower excess air levels than natural draft heaters.

The minimum excess air level is affected by fuel type. Fired heaters combust either gas, oil or a combination of gas and oil. Gas-fired heaters generally require a lower excess air level than oil-fired heaters. Variations in fuel composition such as those often associated with refinery gas may affect the ability of some LEA control systems to continuously maintain the desired excess air. The hydrogen content of the fuel gas at a given refinery may vary from as little as zero percent to as much as 80 percent, causing large variations in heating value. As a result, rapid changes in fuel composition can cause changes in the excess air and/or feedstock outlet temperature before the appropriate fuel flow and damper position corrections can be made.

Leaks which allow air to enter the heater also affect the minimum excess air level attainable in a heater. Oxygen associated with air leakage can be a significant contributor (up to 3 percent O_2)[3] to the measured oxygen content of the flue gas in a poorly maintained heater. However, leakage can be minimized with proper maintenance of the heater. In addition, if low excess air operation is specifically being used for energy conservation or NO_x control, most new heaters can be expected to be properly maintained to minimize air leakage. The majority of the air inleakage occurs above the convective section, thus most LEA control systems monitor oxygen at the top of the radiant section.

The ability of an excess air control system to respond quickly to changes in heater load can be an important factor in determining the long-term average oxygen level that can be maintained in the heater. Although most upstream refinery fired heater applications (e.g. crude heaters) operate essentially under steady state conditions, some downstream units experience periodic load swings that may require special combustion control attention. For example, fired heaters associated with solvent recovery in refinery solvent dewaxing plants are often operated at low and/or widely varying load. Control systems that do not periodically or continuously adjust the combustion air to accommodate load variations in this type of application may exhibit unnecessarily high long term average oxygen levels.[4]

Conventional excess air control systems adjust the combustion air supply by manual damper control. For natural draft heaters, the outlet stack damper is controlled, while for mechanical draft heaters the fan damper on the inlet air plenum is controlled.[5] Flue gas oxygen levels are often not continuously monitored, and damper adjustment of the combustion air supply is infrequent. This can lead to large excess air fluctuations under conditions of varying heater load and/or varying fuel composition. Frequently the damper position is set to provide high excess air under normal operating conditions in order to avoid potentially dangerous oxygen-starved combustion when load and/or fuel composition changes occur. Therefore, on a long-term average basis, the excess air level in a heater with conventional excess air control is often higher than the minimum needed to ensure complete combustion.

Low excess air operation of fired heaters can be achieved by (i) manual damper control systems based on oxygen monitoring and increased operator attention, and (ii) automatic damper control systems based on oxygen monitoring (and/or other process monitoring) and microprocessor control. Manual LEA control systems are described in Section 4.1.1.1 and automatic LEA control systems are described in Section 4.1.1.2.

4.1.1.1 Manual LEA Control Systems--

Manual damper control can be an effective excess air reduction technique provided that the measured heater oxygen level is continuously displayed and the operator has access to stack or fan damper controls. The operator attempts to maintain the oxygen level near a target value by manually adjusting the damper(s). The most important hardware components of the manual damper control systems are the oxygen analyzer, the oxygen recorder, and the damper positioner.

In the simplest manual LEA control system, the heater oxygen level is continuously displayed at the heater site. The operator optimizes the combustion air supply by manually adjusting the damper(s) at discrete time intervals using a chain or pulley apparatus that is also at the heater site. This system is shown in Figure 4-1 for a natural draft heater. Although this system represents an improvement over conventional excess air control because of the continuous oxygen monitoring, the fact that adjustments are made at the heater site is an inherent limitation to the effectiveness of the system. Fired heaters are often located in remote areas of refineries and chemical plants, and operator attention at the heater site is minimal.

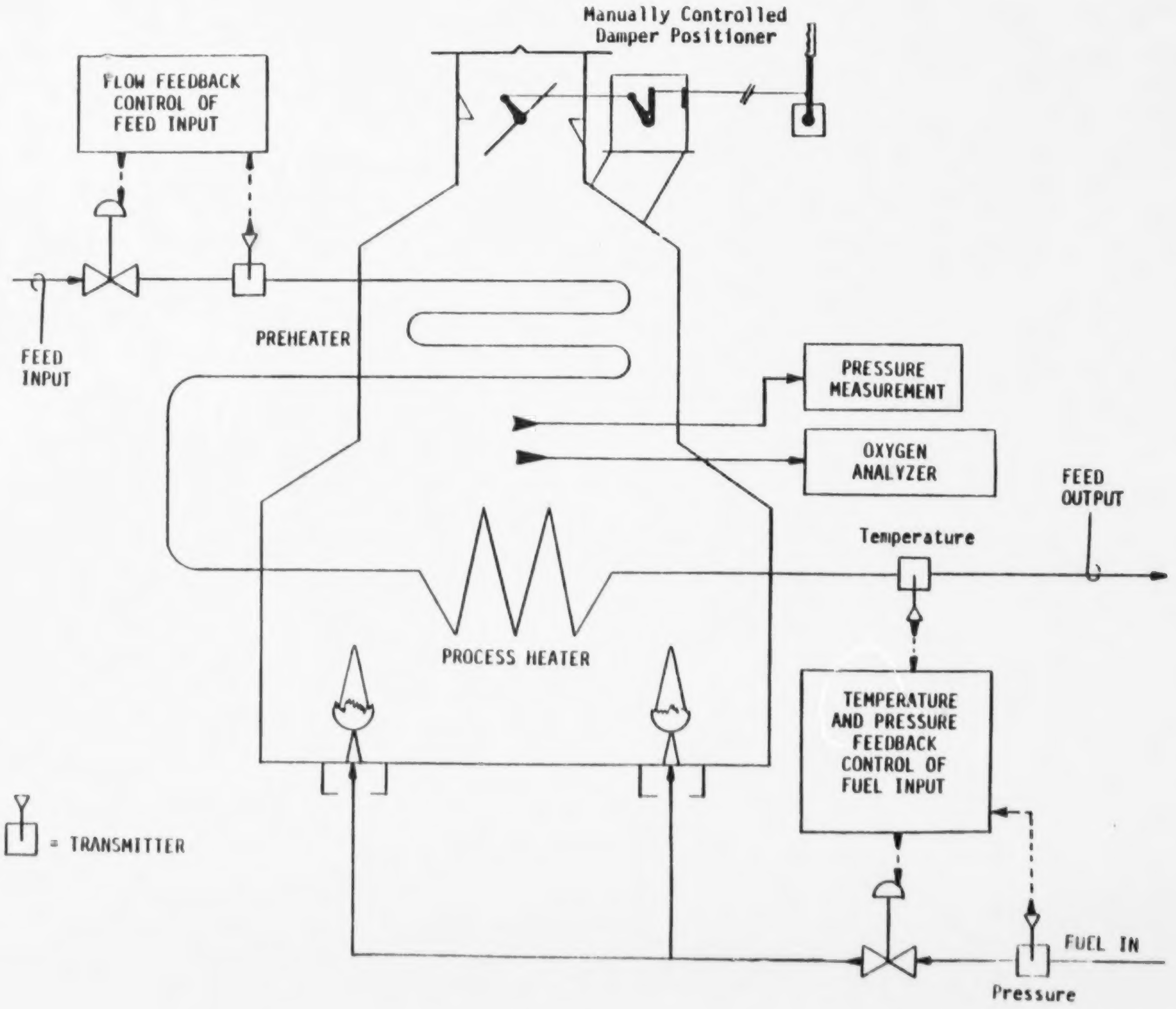

Manually Controlled
Damper Positioner
FLOW FEEDBACK CONTROL OF FEED INPUT
FEED INPUT
PREHEATER
PRESSURE MEASUREMENT
OXYGEN ANALYZER
FEED OUTPUT
Temperature
PROCESS HEATER
TEMPERATURE AND PRESSURE FEEDBACK CONTROL OF FUEL INPUT
= TRANSMITTER
FUEL IN
Pressure

Figure 4-1. Manual LEA control based on draft and oxygen monitoring for a natural draft heater.

In a more complex manual LEA control system, the damper can be adjusted manually from the control room with a remote control damper positioner. The readout from the continuous monitors for draft, damper position, O_2, and possibly combustibles are displayed in the control room. Although optimization of the combustion air is still manual, all the monitor indicators can be clustered with the damper and fuel controls in an easily accessible location. This allows for easier optimization of the combustion air supply at more frequent discrete intervals.[6] The remotely controlled manual damper positioning systems are preferred over those requiring manual damper positioning at the heater site.

4.1.1.2 Automatic LEA Control Systems--

Several types of automatic LEA control systems based on oxygen monitoring or oxygen/carbon monoxide monitoring are commercially available. These systems usually have a setpoint oxygen level programmed into a microprocessor unit, and the damper(s) and/or fuel control valves are automatically adjusted by the microprocessor output to maintain the setpoint oxygen level. To assure safe operation of the heater, the less sophisticated automatic LEA control systems maintain a higher setpoint oxygen level.

When available, large computers that are not fully dedicated can be used to perform the function of the microprocessor. The most important hardware components of automatic LEA control systems are the microprocessor or large computer (controller module), the oxygen or oxygen/carbon monoxide analyzers, the pneumatic or power damper linkages that allow for remote damper control, and the data display unit (i.e. strip chart recorder or CRT display of stack oxygen and other monitored variables).

The simplest automatic LEA control system based on oxygen monitoring is shown in Figure 4-2 and 4-3 for natural draft and mechanical draft heaters, respectively. In this system, the flue gas oxygen content and furnace draft are measured and the output signals are sent to a controller that automatically positions the damper to trim the combustion air flow. The automatic damper positioner is governed by a setpoint oxygen level that is programmed into the controller.[4] The simple automatic LEA control system based on

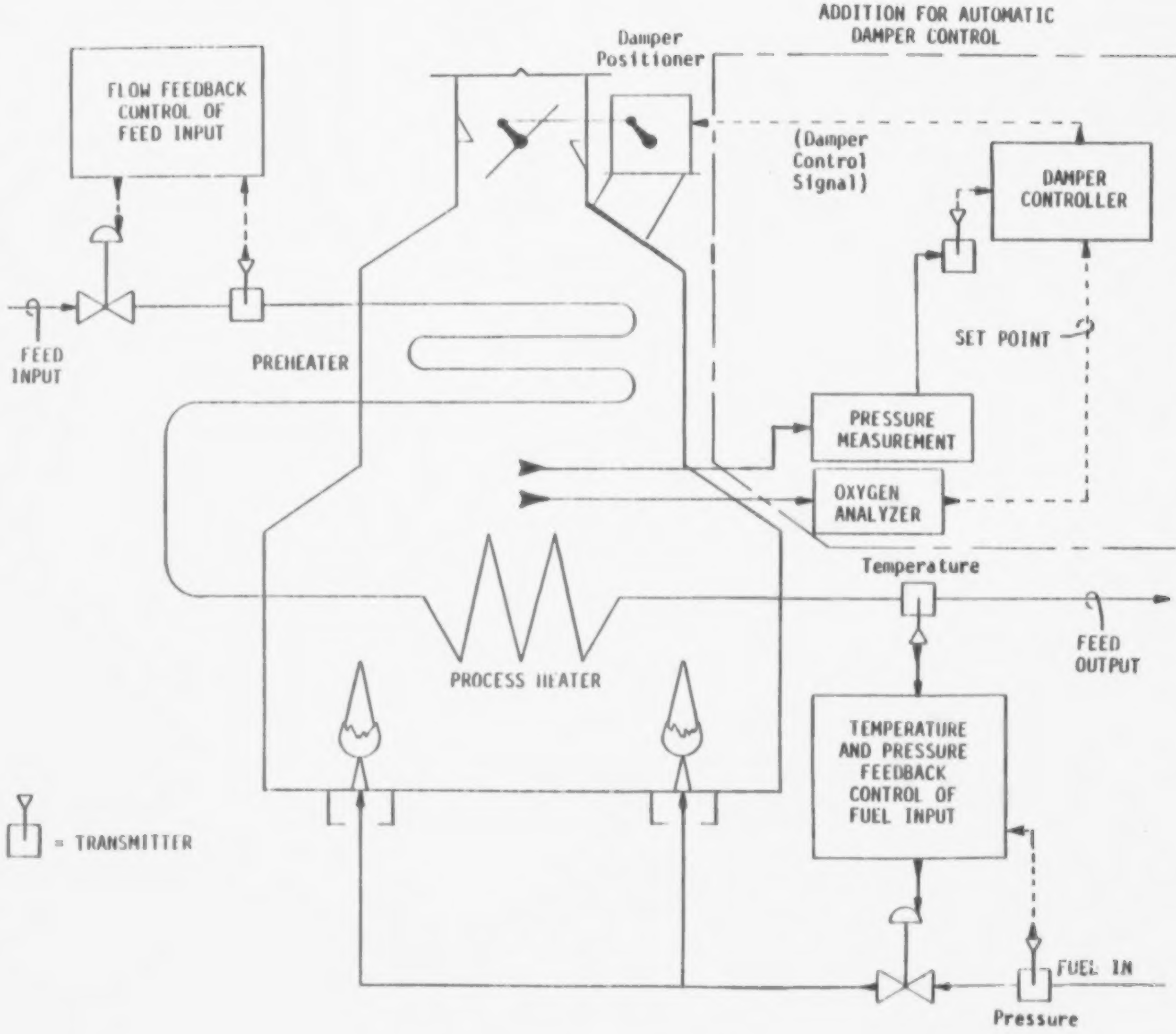

ADDITION FOR AUTOMATIC DAMPER CONTROL
Damper Positioner
FLOW FEEDBACK CONTROL OF FEED INPUT
(Damper Control Signal)
DAMPER CONTROLLER
SET POINT
FEED INPUT
PREHEATER
PRESSURE MEASUREMENT
OXYGEN ANALYZER
Temperature
FEED OUTPUT
PROCESS HEATER
TEMPERATURE AND PRESSURE FEEDBACK CONTROL OF FUEL INPUT
= TRANSMITTER
FUEL IN
Pressure

Figure 4-2. Automatic LEA control based on oxygen and draft monitoring for a natural draft heater.

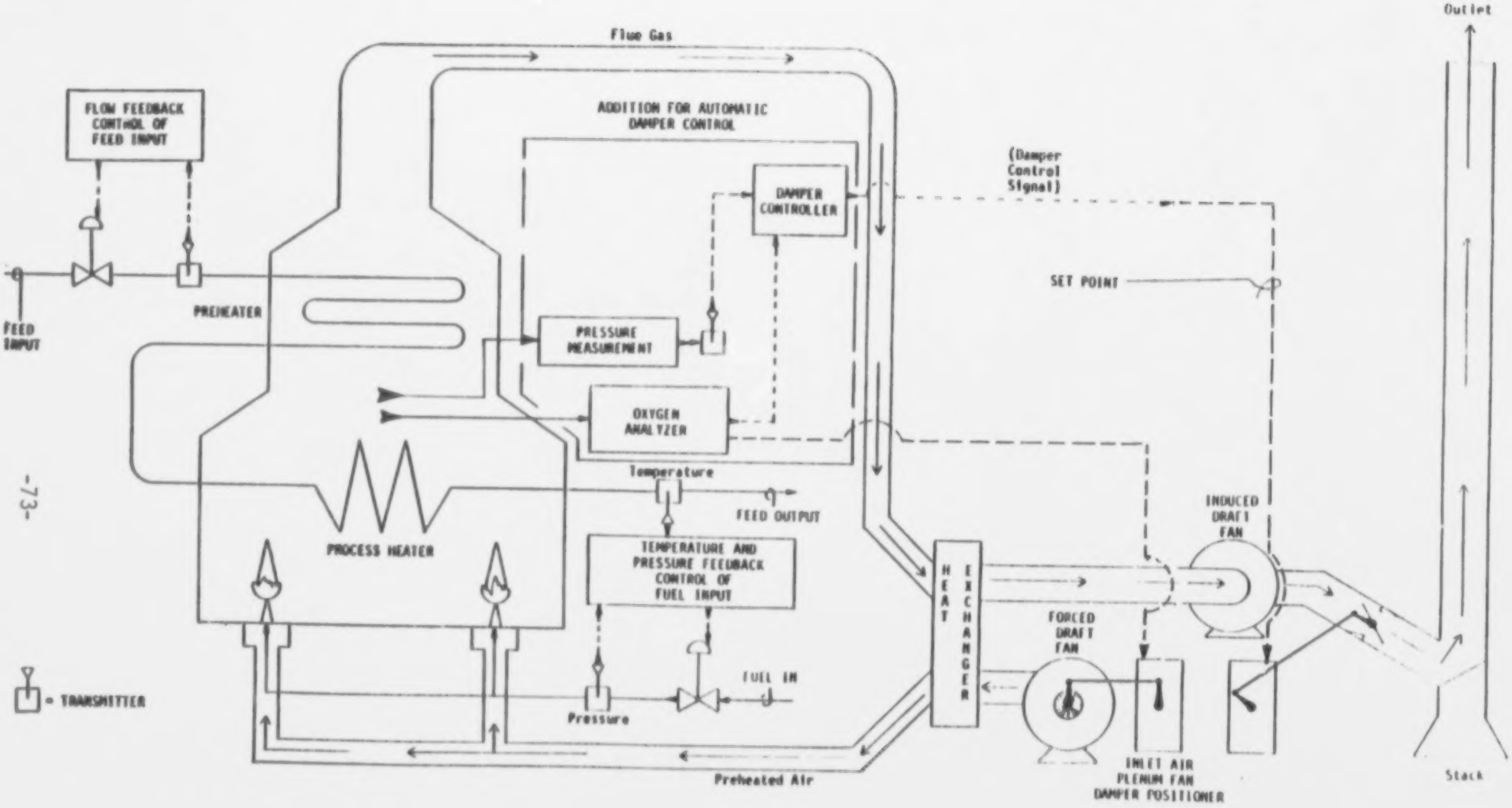

Flue Gas
FLOW FEEDBACK CONTROL OF FEED INPUT
ADDITION FOR AUTOMATIC DAMPER CONTROL
(Damper Control Signal)
DAMPER CONTROLLER
SET POINT
PREHEATER
FEED INPUT
PRESSURE MEASUREMENT
OXYGEN ANALYZER
Temperature
FEED OUTPUT
PROCESS HEATER
TEMPERATURE AND PRESSURE FEEDBACK CONTROL OF FUEL INPUT
INDUCED DRAFT FAN
HEAT EXCHANGER
FORCED DRAFT FAN
= TRANSMITTER
Pressure
FUEL IN
Preheated Air
INLET AIR PLENUM FAN DAMPER POSITIONER
Outlet
Stack

Figure 4-3. Automatic LEA control based on oxygen and draft monitoring for a mechanical draft heater.

oxygen and draft monitoring is more effective in maintaining low excess air than the remote-manual LEA control systems due to the continual correction of the damper position. However, the effectiveness of the simple automatic LEA systems shown in Figure 4-2 and 4-3 may be limited in situations where the fuel flow and/or fuel composition changes rapidly. The simple LEA system does not integrate the fuel flow measurement into the control of the damper.

The LEA control system shown in Figure 4-4 is a metered fuel and air flow control system that includes an oxygen trim fuel controller to compensate for variations in the heating value of the fuel. Figure 4-4 shows the LEA control system applied to a natural draft heater, but it is equally applicable to mechanical draft heaters with and without combustion air preheat. In this system the measured oxygen content in the flue gas is not used to control the damper(s) directly. Instead, the measured oxygen content is used to trim the fuel flow while the damper is positioned according to the feed flowrate, the feed outlet temperature and the furnace draft. This system is reported to improve the control of feed outlet temperature and excess air under conditions of varying fuel heating value, relative to the simpler system shown in Figures 4-2 and 4-3. Stack oxygen is more responsive to variations in fuel composition than to variations in outlet feedstock temperatures. The setpoint oxygen level can usually be selected by the operator at the control panel. It can vary from heater to heater depending on process conditions and operator preference.[7]

The most advanced commercially available LEA control systems employ both oxygen and carbon monoxide monitoring to control excess air. The carbon monoxide level is monitored because it is a very sensitive indicator of furnace operation when the heater is operated near the minimum excess air level. A schematic diagram of one example of this type of system is shown in Figure 4-5. It operates on the basis of a "constraint control" concept that employs measurements of flue gas oxygen content, flue gas carbon monoxide content, furnace draft, tube skin temperature, and fuel flow. The microprocessor scans all of the measurements and opens the damper to relieve any constraint conditions which are defined by deviations of the parameters

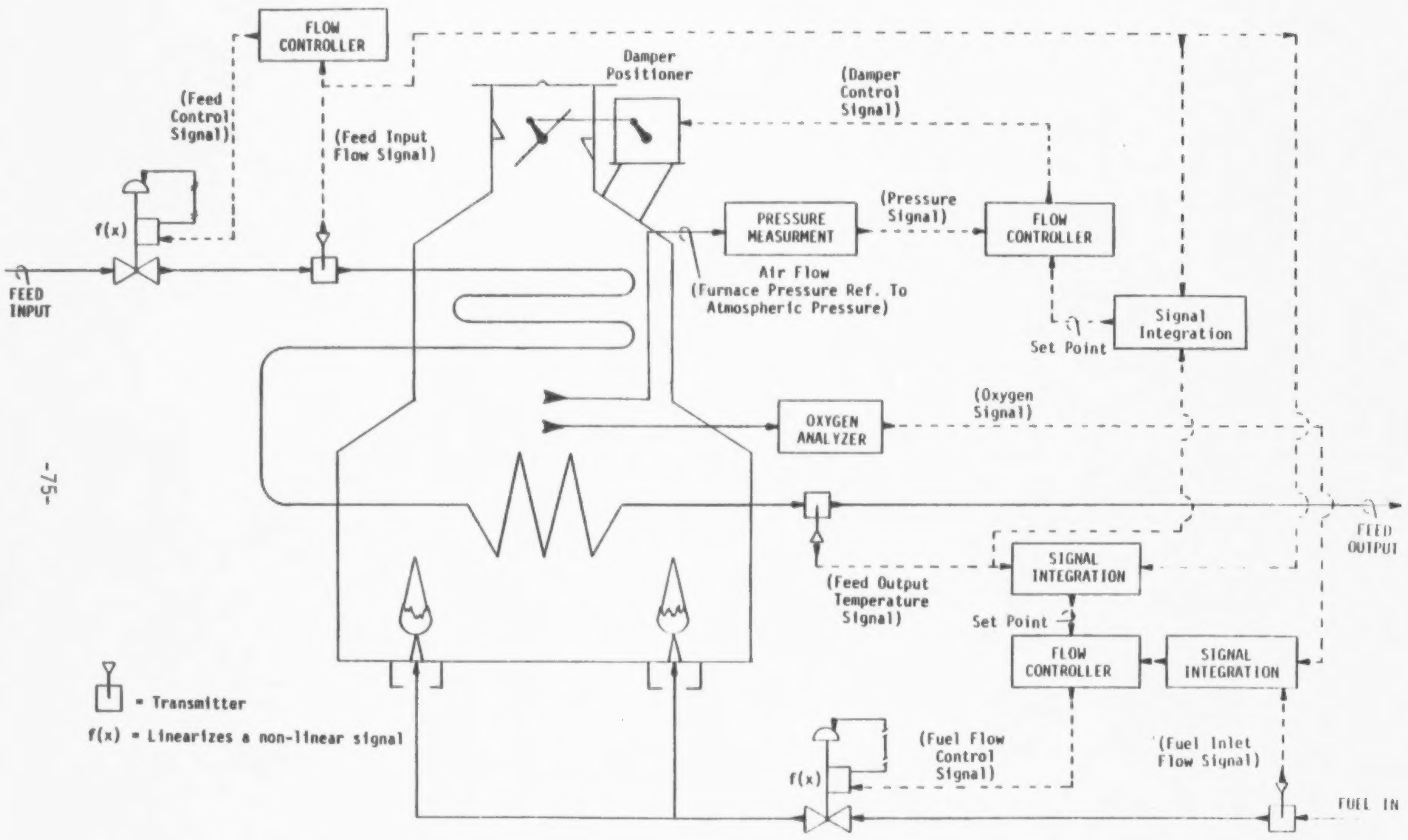
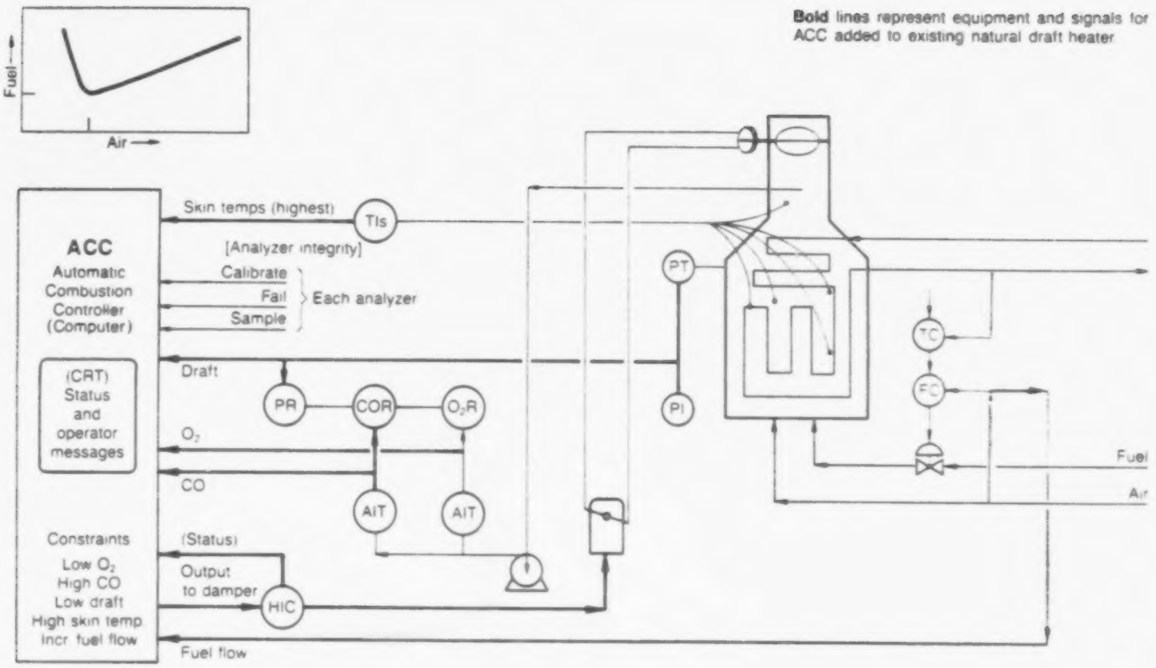

FLOW CONTROLLER
(Feed Control Signal)
(Feed Input Flow Signal)
Damper Positioner
(Damper Control Signal)
f(x)
FEED INPUT
PRESSURE MEASURMENT
(Pressure Signal)
FLOW CONTROLLER
Air Flow
(Furnace Pressure Ref. To Atmospheric Pressure)
Signal Integration
Set Point
OXYGEN ANALYZER
(Oxygen Signal)
FEED OUTPUT
SIGNAL INTEGRATION
(Feed Output Temperature Signal)
Set Point
FLOW CONTROLLER
SIGNAL INTEGRATION
(Fuel Flow Control Signal)
(Fuel Inlet Flow Signal)
f(x)
FUEL IN
= Transmitter
f(x) = Linearizes a non-linear signal

Figure 4-4. Automatic LEA control based on metered fuel and airflow for a natural draft heater. Adapted from reference 7.



Bold lines represent equipment and signals for ACC added to existing natural draft heater

Fuel
Air
ACC
Automatic
Combustion
Controller
(Computer)
(CRT)
Status
and
operator
messages
Constraints
Low O_2
High CO
Low draft
High skin temp
Incr. fuel flow
Skin temps (highest)
TIs
[Analyzer integrity]
Calibrate
Fail
Sample
Each analyzer
Draft
PR
COR
O_2R
O_2
CO
AIT
AIT
(Status)
Output
to damper
HIC
Fuel flow
PT
PI
TC
FC
Fuel
Air

Figure 4-5. Schematic of the Automatic Combustion Control System (ACC)* based on oxygen and carbon monoxide monitoring.[8]

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from their setpoint values. Once the constraint condition is relieved, the controller starts closing the damper until another constraint condition occurs. This method ensures maximum combustion efficiency under constantly changing process conditions. The type of LEA control system shown in Figure 4-5 was tested on a natural draft heater. The 35-day average oxygen level was reported to be 1.6 percent oxygen (measured at the top of the convective section). The long term average oxygen level achieved on the same heater by careful manual control using remote damper positioning was reported to be 3.5 percent oxygen (measured at the top of the convective section). Thus, the advanced LEA control system reduced the long term average oxygen level by 1.9 percent oxygen relative to the minimum level achievable using the remote control manual LEA system.[8]

4.1.2 Applicability

The available information suggests that automatic LEA controls based on flue gas monitoring (oxygen alone or oxygen and carbon monoxide together) are applicable to all new fired heaters. Manual and automatic damper control systems designed to reduce excess air can be used with natural or mechanical draft and with gas, oil, or gas/oil combinations. At present, automatic LEA control systems based on oxygen monitoring only are in use on at least 10 fired heaters,[9] and automatic LEA control systems based on oxygen and carbon monoxide monitoring are in use on at least 45 fired heaters.[10] Manual LEA control systems based on oxygen monitoring are in use on many other heaters. For the purpose of energy conservation one major refining company has committed to installing automatic LEA controls based on oxygen and carbon monoxide monitoring on all new fired heaters larger than 50 MMBtu/hr.[11]

Commercially packaged automatic damper control systems may not be directly applicable to some specific heater applications. One example of this is multicell heaters with common convection zones and one or more stacks when the cells are not well balanced with respect to variations in product charge and fuel firing rates. In these cases, the basic packaged control systems may require some modification or compromise in achieving minimum low excess air. It is expected that appropriate modifications can be made for all such applications. Therefore, LEA controls are considered applicable to all new fired heaters.

4.1.3 Performance Data

The assessment of the effectiveness of LEA control systems in reducing NO_x emissions from fired heaters is based on the average of the NO_x emissions reductions achieved on the 12 heaters for which long-term continuous monitoring NO_x emissions data were obtained in this study. The NO_x reduction is evaluated by mathematically modeling the relationship between NO_x and stack oxygen level based on the continuous NO_x and O_2 monitoring data in the data base. A representative model of the long-term average relationship between NO_x and stack oxygen level can be developed using long term continuous monitoring data. The model statistically accounts for variations in load and fuel composition. Heater operations vary significantly from day to day and therefore short term spot test data are not useful for this purpose.

The following sections describe the continuous monitoring NO_x emissions data base (Section 4.1.3.1), the analysis of the data (Section 4.1.3.2), the predicted NO_x emissions based on the model (Section 4.1.3.3) and the NO_x emission reductions achieved (Section 4.1.3.4).

4.1.3.1 Description of the Long Term Continuous Monitoring NO_x Emissions Data Base--

The description of the continuous monitoring data base is divided into two parts: (i) a description of the heaters in the data base and (ii) a description of the NO_x monitoring data obtained from the heaters.

The heaters in the data base are summarized in Table 4-2. A total of twelve heaters from three refineries are represented. The plants from which the data were obtained monitor NO_x and O_2 at the stack for regulatory compliance purposes. The heaters are grouped in Table 4-2 by fuel type, burner type and draft type characteristics. The data base includes ten

TABLE 4-2. DESCRIPTION OF HEATERS IN THE LONG TERM CONTINUOUS MONITORING NO_x EMISSIONS DATA BASE

Heater Code	Heater/Burner[a] Classification	Plant Heater Designation	Heater Application	Heater Capacity (MMBtu/hr)	Number Of Burners	Burner Manufacturer	Burner Model No.	Data Source[b]
A	G - RGB - ND	F-20	Vacuum Crude	28.7	Six	National Airoil	#30 FA VHESP	1
B	G - RGB - ND	F-603	Naptha Desulfurizer	9.8	One	John Zink	VYD-PC-22	1
C	G - PMB - ND	F-601	Naptha Reformer	70.8	Seventy	John Zink	VPM-12	1
D	G - PMB - ND	F-602	Desulfurizer	18.4	Four	John Zink	VDPM-18	1
E	G - PMB - ND	F-602	Gas-Oil	18.4	Four	John Zink	VDPM-18	1
F	G - SAB - ND	9H1 - 9H4 (common stack)	Reformer Charge	87.0	Fifteen	John Zink	DBA[c]	2
G	G - SAB - ND	12 - H1	Light Ends	39.6	Eight	John Zink	LN-PC-14	2
H	G - SAB - ND	-	Atmospheric Crude	18	Three	John Zink	LNC-16	3
I	G - SAB - ND	F-1	Atmospheric Crude	86.3	Eight One	John Zink John Zink	MA-PC-16[d] MA-PC-20[d]	1 1
J	G - RGB - MD/PH	F-603	Naptha Desulfurizer	9.8	One	John Zink	PLNV-50	1
K	O/G - SAB - ND	10 - H1	Atmospheric Crude	110.6	Eight	John Zink	LN-PC-18	2
L	O/G - SAB - ND	11 - H1	Atmospheric Crude	37.0	Four	John Zink	LN-PC-16	2

a. Fuel Type - burner type - draft type/preheat.
notation: G = gas-fired; O/G = Combination of oil and gas fired;
RGB = conventional raw gas burner; PMB = conventional premix burner;
SAB = staged air burner; ND = natural draft; MD = mechanical draft;
PH = combustion air preheat.

b. Data Source Key
1 = USA Petrochem refinery in Ventura, California.
2 = Getty Refining and Marketing Company refinery in Bakersfield, CA.
3 = U. S. EPA/IERL, Research Triangle Park, NC (Reference 12)

c. Modified with Steam Injection for Lower NO_x Production.

d. Modified with Air Staging for Lower NO_x Production.

gas-fired heaters and two combined gas/oil fired heaters with up to 30 percent oil-firing on an energy basis. Also, three of the heaters in the data base have conventional raw gas burners, three heaters have premix burners, and six heaters have staged air low-NO_x burners. Eleven of the heaters are natural draft and one is mechanical draft with preheat. Excess air control for all of the heaters was performed using remote, manual damper control based on oxygen monitoring in the stack. The heaters in the data base represent seven low or medium temperature refinery process applications. Their capacities range from 10 to 110 MMBtu/hr, spanning the lower to middle range of heater size. Thus, as a whole the heaters represent a wide range of design characteristics and process applications.

The continuous NO_x and O_2 monitoring data are summarized in Table 4-3. Sample raw data sheets of the continuous monitoring data for the three refineries are presented in Appendix B. For each data set, the average values of the stack oxygen level, NO_x emissions and fuel firing rate are tabulated. The long term average stack oxygen level measured for individual heaters ranged from 2 percent O_2 to 9 percent O_2. The fuel firing rate ranged from 4 to 120 MMBtu/hr, representing a fractional load variation from 40 to 120 percent of heater capacity.

4.1.3.2 Analysis of the Continuous NO_x Monitoring Data--

The continuous NO_x monitoring data from each heater was statistically fit to a mathematical model that correlates the relationship of NO_x emissions to stack oxygen level, heater load, degree of oil-firing and fuel gas hydrogen content. The model was then used to isolate the relationship of excess oxygen level to NO_x emissions.

Ideally, the excess oxygen level measured at the top of the radiant section should be used to correlate NO_x to O_2. However, the CEM data available from industrial sources measured the excess oxygen level at the stack. The stack excess oxygen level includes an undetermined amount of air inleakage which acts to dampen the NO_x/O_2 response. Thus, the heaters in the data base may actually have a greater NO_x/O_2 relationship than determined in this analysis.

TABLE 4-3. SUMMARY OF DATA IN THE LONGTERM CONTINUOUS MONITORING NO_X EMISSIONS DATA BASE

Heater Code	Heater/Burner[a] Classification	Test Period	Parameter	Number[c] Data Points	Average	Range	Standard Deviation
A	G - RGB - ND	11/81 to 4/82	Stack O_2 (%)	3448	5.06	0.3-12.3	1.92
			Fuel Firing Rate (MMBtu/hr)	3445	23.6	13.2-40.4	6.94
			NO_x Emissions (lb/MMBtu)	3445	0.11	0.03-0.24	0.042
B	G - RGB - ND	11/81 to 12/81	Stack O_2 (%)	1399	8.76	1.4-15.7	3.10
			Fuel Firing Rate (MMBtu/hr)	1401	5.6	2.1-7.1	0.45
			NO_x Emissions (lb/MMBtu)	1399	0.10	0.03-0.17	0.026
C	G - PMB - ND	7/78 to 12/78	Stack O_2 (%)	2096	3.15	0.1-17.0	1.43
			Fuel Firing Rate (MMBtu/hr)	3095	48.9	13.0-65.0	6.4
			NO_x Emissions (lb/MMBtu)	3095	0.09	0-0.28	0.033
		11/81 to 4/82	Stack O_2 (%)	3321	3.81	0.3-12.9	1.75
			Fuel Firing Rate (MMBtu/hr)	3321	32.0	18.0-43.1	2.8
			NO_x Emissions (lb/MMBtu)	3321	0.10	0.01-0.27	0.03
D	G - PMB - ND	7/78 to 12/78	Stack O_2 (%)	3088	2.85	0.2-16.5	1.65
			Fuel Firing Rate (MMBtu/hr)[b]	3096	7.6	0.5-12.3	1.5
			NO_x Emissions (lb/MMBtu)	3084	0.10	0.004-0.29	0.028
E	G - PMB - ND	11/81 to 4/82	Stack O_2 (%)	3035	8.52	1.7-16.0	3.19
			Fuel Firing Rate (MMBtu/hr)	3034	8.1	4.7-13.2	1.4
			NO_x Emissions (lb/MMBtu)	3030	0.13	0.005-0.26	0.046
F	G - SAB - ND	2/81 to 10/81	Stack O_2 (%)	1079	5.5	2.7-8.4	1.4
			Fuel Firing Rate (MMBtu/hr)	1084	71.3	4.7-83.8	5.9
			Gas Fuel H_2 Content (%)	1149	39.1	30.1-49.6	6.6
(Heater F continued on next page)			NO_x Emissions (lb/MMBtu)	1076	0.10	0.05-0.16	0.02

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[a] See Table 4-2, footnote (a) for explanation of notation.

[b] Based on fuel gas meter reading and assuming 1000 Btu/scf.

[c] Number of hourly averages.

TABLE 4-3. (Continued)

Heater Code	Heater/Burner[a] Classification	Test Period	Parameter	Number[c] Data Points	Average	Range	Standard Deviation
		3/82 to 4/82	Stack O_2 (%)	547	7.3	3.7-9.1	1.8
			Fuel Firing Rate (MMBtu/hr)	546	72.1	12.7-96.3	2.8
			Gas Fuel H_2 Content (%)	712	45.0	40.1-50.5	3.7
			NO_x Emissions (lb/MMBtu)	533	0.12	0.09-0.17	0.03
G	G - SAB - ND	3/82 to 4/82	Stack O_2 (%)	544	4.4	1.6-12.4	1.2
			Fuel Firing Rate (MMBtu/hr)	544	35.4	6.0-77.6	5.6
			Gas Fuel H_2 Content (%)	712	45.0	40.1-50.5	3.7
			NO_x Emissions (lb/MMBtu)	544	0.13	0.07-0.18	0.02
H	G - SAB - ND	7/81 to 9/81	Stack O_2 (%)	2786	5.85	0.80-14.0	1.9
			Fuel Firing Rate (MMBtu/hr)	2827	14.16	0.0-16.83	1.6
			NO_x Emissions (lb/MMBtu)	2786	0.103	0.003-0.133	0.012
I	G - SAB - ND	7/78 to 12/78	Stack O_2 (%)	2987	2.11	0.1-19.0	2.09
			Fuel Firing Rate[b] (MMBtu/hr)	2997	56.0	6.9-69.3	7.7
			NO_x Emissions (lb/MMBtu)	2987	0.08	0.008-0.16	0.021
J	G - RGB - MD/PH	1/82 to 4/82	Stack O_2 (%)	1887	9.04	0.6-17.8	3.61
			Fuel Firing Rate (MMBtu/hr)	1888	3.9	2.6-6.3	0.51
			NO_x Emissions (lb/MMBtu)	1877	0.22	0.07-0.37	0.049
		7/84 to 8/84	Stack O_2 (%)	721	5.77	1.1-11.0	1.85
			Fuel Firing Rate (MM Btu/hr)	721	4.05	2.67-6.19	1.07
			NO_x Emissions (lb/MMBtu)	721	0.180	0.046-0.309	0.045

[a] See Table 4-2, footnote (a) for explanation of notation.

[b] Based on fuel gas meter reading and assuming 1000 Btu/scf.

[c] Number of hourly averages.

TABLE 4-3. (Continued)

Heater Code	Heater/Burner[a] Classification	Test Period	Parameter	Number[c] Data Points	Average	Range	Standard Deviation
K	O/G - SAB - ND	2/81 to 10/81	Stack O_2 (%)	933	3.5	1.0-9.0	1.5
			Fuel Firing Rate[b] (MMBtu/hr)	934	122.1	19.8-136.7	10.5
			Gas Fuel H_2 Content (%)	1090	43.4	6.6-61.7	18.7
			Oil: Gas Ratio (%)	934	31.0	20.0-45.0	4.0
			NO_x Emissions (lb/MMBtu)	933	0.12	0.07-0.16	0.02
		3/82 to 4/82	Stack O_2 (%)	541	4.1	1.1-9.3	0.8
			Fuel Firing Rate[b] (MMBtu/hr)	414	96.4	45.8-171.0	9.3
			Gas Fuel H_2 Content (%)	712	45.0	40.1-50.5	3.7
			Oil: Gas Ratio (%)	414	18.3	2.2-51.4	6.6
			NO_x Emissions (lb/MMBtu)	392	0.14	0.10-0.18	0.02
L	O/G - SAB - ND	2/81 to 10/81	Stack O_2 (%)	757	3.9	0.9-11.4	1.6
			Fuel Firing Rate[b] (MMBtu/hr)	758	27.3	19.8-44.5	4.1
			Gas Fuel H_2 Content (%)	935	41.2	6.6-61.7	20.3
			Oil: Gas Ratio (%)	758	6.0	0.0-40.0	8.0
			NO_x Emissions (lb/MMBtu)	757	0.07	0.04-0.12	0.01
		3/82 to 4/82	Stack O_2 (%)	541	3.9	0.4-12.1	1.2
			Fuel Firing Rate[b] (MMBtu/hr)	541	19.0	3.6-36.1	3.3
			Gas Fuel H_2 Content (%)	712	45.0	40.1-50.5	3.7
			Oil: Gas Ratio (%)	541	13.2	0.02-45.4	10.9
			NO_x Emissions (lb/MMBtu)	541	0.10	0.06-0.21	0.02

[a] See Table 4-2, footnote (a) for explanation of notation.

[b] Based on fuel gas meter reading and assuming 1000 Btu/scf.

[c] Number of hourly averages.

The NO_x/O_2 relationships developed are used in Section 4.1.3.4 to evaluate the NO_x emission reduction potential of LEA controls. A multiplicative functional form based on the Zeldovich mechanism for thermal NO_x formation (Section 4.2.1.1) was found to adequately correlate the data.

The basic form of the model used is:

$$E = C_1 L^{C_2} A^{C_3} (1+R)^{C_4} (1+H)^{C_5}$$

where: E = NO_x emissions (lb/MM Btu)

L = fuel firing rate expressed as a fraction of the design thermal energy release

$$\left(L = \frac{\text{fuel firing rate, Btu/hr}}{\text{design thermal capacity, Btu/hr}} \right)$$

A = stack oxygen (volume fraction of O_2)

R = oil fraction, ratio of oil-fired heat release to total fuel-fired heat release. When no oil is fired, R = 0 and model parameter C_4 has no meaningful value.

H = fuel gas hydrogen content (volume fraction of H_2). When no fuel gas hydrogen data are available, model parameter C_5 is assigned a value of zero.

C_1, C_2, C_3, C_4, and C_5 = model coefficients that indicate the effect of the corresponding variables on NO_x emissions.

The model coefficients were fit to the NO_x emissions data using a statistical procedure known as autocorrelative regression. The autoregressive model accounts for any effects on the coefficients of autocorrelation associated with the sequential nature of the data. In several cases (heaters A, C, E, F, J, K, and L) the data from a long time period for a given heater were separated into two distinct parts by a data gap in the middle, and the data from the two distinct parts were analyzed individually.

In other cases (heaters A, B, C, E, F, G, K, and L) an initial analysis showed one or more of the model parameters to be statistically insignificant, and the regression analysis was run both with and without the corresponding factor included. A parameter was judged statistically insignificant if its 95 percent confidence interval contained zero. In all cases, exclusion of the factor whose coefficient was found to be statistically insignificant did not affect the fit of the regression model to the data. Coefficients C_2 (heater load) and C_5 (fuel gas H_2) were frequently found to be statistically insignificant. The statistical analysis methodology is described in Appendix C.

The coefficients and coefficient of determination for each heater model are presented in Table 4-4. The coefficient of determination is an indication of how well the model fit the data. The coefficients of determination were in the 0.70 to 0.95 range for these models, which are considered good.

4.1.3.3 Predicted NO_x Emissions from the Heater Models--

For each heater model, NO_x emissions were predicted at variable stack oxygen levels while the heater load, degree of oil-firing and fuel gas hydrogen content were held constant. The NO_x emission levels predicted by the models at 2 percent, 3 percent, 4 percent, 5 percent and 5.5 percent stack oxygen are tabulated in Table 4-5. The heaters in the data base typically operated in this range of oxygen levels, with the average oxygen level being 5.5 percent. The minimum excess oxygen level is assumed to be 3 percent for natural draft heaters and 2 percent for mechanical draft heaters. The minimum achievable excess oxygen level is defined as the lowest excess oxygen level where the heater is operating in an acceptable manner and at a reasonable CO level. The heater load was set at 100 percent, and the constant values for degree of oil-firing and fuel gas hydrogen content are indicated in the table where appropriate.

4.1.3.4 NO_x Emissions Reductions Evaluated from the Data and Effectiveness of Low Excess Air Control Systems--

The NO_x emissions reductions were evaluated for each heater by calculating the percent reduction in NO_x emissions per percent reduction in

TABLE 4-4. MODEL COEFFICIENTS FOR ANALYZED HEATERS IN THE LONG TERM CONTINUOUS MONITORING NO_x EMISSIONS DATA BASE

Heater Code	Heater/Burner Classification[a]	Test Period	Modeling Coefficients C_1	C_2	C_3	C_4	C_5	Coefficient of Determination R^2
A	G - RGB - ND	11/81 to 4/82 First Part	0.47	0.06[b]	0.41	-	-	-
			0.46	-	0.41	-	-	0.92
		Second Part	0.42	-0.20	0.55	-	-	0.95
B	G - RGB - ND	11/81 to 12/81	0.20	-0.03[b]	0.30	-	-	-
			0.20	-	0.28	-	-	0.93
C	G - PMB - ND	7/78 to 12/78	0.42	0.014	0.44	-	-	0.84
		11/81 to 4/82 First Part	1.08	0.39	0.73	-	-	0.82
		Second Part	3.20	0.16[b]	0.92	-	-	-
			2.78	-	0.92	-	-	0.86
D	G - PMB - ND	7/78 to 12/78	0.29	0.091	0.28	-	-	0.87
E	G - PMB - ND	11/81 to 4/82 First Part	0.27	0.05[b]	0.31	-	-	-
			0.27	-	0.31	-	-	0.90
		Second Part	1.53	-0.06[b]	0.96	-	-	-
			1.56	-	0.96	-	-	0.98
F	G - SAB - ND	2/81 to 10/81 First Part	0.52	-0.004[b]	0.60	-	0.66	-
			0.52	-	0.60	-	0.66	0.70
		Second Part	0.83	-0.01[b]	0.69	-	-0.55	-
			0.83	-	0.70	-	-0.55	0.90
		3/82 to 4/82	0.33	0.007[b]	0.29	-	-0.71[b]	-
			0.25	-	0.28	-	-	0.83

[a] See Table 4-2, footnote (a) for explanation of notation.

[b] Coefficient found to be statistically insignificant at the 95% confidence level.

TABLE 4-4. (Continued)

Heater Code	Heater/Burner Classification[a]	Test Period	Modeling Coefficients C_1	C_2	C_3	C_4	C_5	Coefficient of Determination R^2
G	G - SAB - ND	3/82 to 4/82	0.48	-0.002[b]	0.37	-	-0.49[b]	-
			0.40	-	0.37	-	-	0.89
H	G - SAB - ND	8/81 to 9/81	0.19	-	0.18	-	-	0.85
I	G - SAB - ND	7/78 to 12/78	0.19	0.56	0.15	-	-	0.81
J	G - RGB - MD/PH	1/82 to 4/82	0.75	0.14	0.46	-	-	0.94
		7/84 to 8/84	1.39	0.38	0.59	-	-	0.51
K	O/G - SAB - ND	2/82 to 10/81	0.33	0.01[b]	0.29	-0.04[b]	-0.15	-
			0.32	-	0.29	-	-0.14	0.95
		3/82 to 4/82	0.54	-0.006[b]	0.32	0.45	-1.03	-
			0.54	-	0.32	0.46	-1.00	0.82
L	O/G - SAB - ND	2/81 to 10/81 First Part	0.16	-0.51	0.26	-1.16	-0.27[b]	-
			0.15	-0.51	0.26	-1.17	-	0.94
		Second Part	0.16	-0.35	0.29	0.63	-0.13[b]	-
			0.15	-0.37	0.29	0.69	-	0.94
		3/82 to 4/82	0.35	0.08	0.36	1.51	-0.46[b]	-
			0.29	0.08	0.36	1.56	-	0.93

[a] See Table 4-2, footnote (a) for explanation

[b] Coefficient found to be statistically insignificant at the 95% confidence level.

TABLE 4-5. VARIATION OF NO_X EMISSIONS WITH STACK OXYGEN FOR HEATERS IN THE LONG TERM CONTINUOUS MONITORING NO_X EMISSIONS DATA BASE

Heater Code	Heater/Burner Classification[a]	Test Period	Predicted NO_x Emissions at Full Load and Varying Stack Oxygen Levels, (lb/MMBtu)[b]				
			2% O_2	3% O_2	4% O_2	5% O_2	5.5% O_2
A	G - RGB - ND	11/81 to 4/82 First Part	0.091 (0.086, 0.096)	0.107 (0.102, 0.113)	0.121 (0.115, 0.127)	0.133 (0.126, 0.140)	0.140 (0.133, 0.147)
		Second Part	0.049 (0.048, 0.051)	0.062 (0.059, 0.064)	0.072 (0.070, 0.075)	0.082 (0.079, 0.084)	0.085 (0.082, 0.087)
B	G - RGB - ND	11/81 to 12/81	0.065 (0.060, 0.070)	0.073 (0.068, 0.078)	0.079 (0.074, 0.084)	0.084 (0.079, 0.089)	0.089 (0.084, 0.094)
C	G - PMB - ND	7/78 to 12/78	0.074 (0.069, 0.079)	0.089 (0.083, 0.095)	0.101 (0.094, 0.108)	0.111 (0.104, 0.119)	0.117 (0.109, 0.125)
		11/81 to 4/82 First Part	0.061 (0.051, 0.073)	0.082 (0.069, 0.098)	0.101 (0.085, 0.122)	0.120 (0.100, 0.143)	0.130 (0.110, 0.150)
		Second Part	0.076 (0.073, 0.080)	0.111 (0.105, 0.166)	0.144 (0.137, 0.152)	0.177 (0.168, 0.187)	0.193 (0.183, 0.203)
D	G - PMB - ND	7/78 to 12/78	0.097 (0.093, 0.100)	0.108 (0.104, 0.122)	0.117 (0.113, 0.122)	0.125 (0.120, 0.130)	0.129 (0.124, 0.134)
E	G - PMB - ND	11/81 to 4/82 First Part	0.081 (0.070, 0.093)	0.092 (0.081, 0.104)	0.100 (0.090, 0.112)	0.108 (0.097, 0.119)	0.110 (0.099, 0.121)
		Second Part	0.036 (0.031, 0.042)	0.054 (0.046, 0.062)	0.071 (0.061, 0.082)	0.088 (0.076, 0.101)	0.096 (0.083, 0.154)
F	G - SAB - ND	2/81 to 10/81 First Part (H_2 = 37.4%)	0.060 (0.050, 0.073)	0.077 (0.068, 0.088)	0.092 (0.085, 0.100)	0.105 (0.100, 0.111)	0.113 (0.107, 0.119)
		Second Part (H_2 - 39.8%)	0.046 (0.043, 0.048)	0.060 (0.058, 0.063)	0.074 (0.072, 0.076)	0.086 (0.084, 0.088)	0.091 (0.089, 0.093)
		3/82 to 4/82	0.083 (0.074, 0.092)	0.093 (0.086, 0.100)	0.101 (0.095, 0.106)	0.107 (0.103, 0.112)	0.111 (0.106, 0.116)

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[a] See Table 4-2, footnote (a) for explanation of notation.

[b] The 95% confidence interval for each predicted value is given in parenthesis.

TABLE 4-5. (Continued)

Heater Code	Heater/Burner Classification[a]	Test Period	Predicted NO_x Emissions at Full Load and Varying Stack Oxygen Levels, (lb/MBtu)[b] 2% O_2	3% O_2	4% O_2	5% O_2	5.5% O_2
G	G - SAB - ND	3/82 to 4/82	0.093 (0.091, 0.096)	0.109 (0.106, 0.111)	0.121 (0.118, 0.124)	0.131 (0.128, 0.135)	0.137 (0.133, 0.141)
H	G - SAB - ND	8/81 to 9/81	0.093 (0.064, 0.122)	0.100 (0.071, 0.129)	0.106 (0.078, 0.134)	0.110 (0.082, 0.138)	0.112 (0.084, 0.140)
I	G - SAB - ND	7/78 to 12/78	0.104 (0.099, 0.109)	0.111 (0.105, 0.116)	0.116 (0.110, 0.122)	0.119 (0.113, 0.126)	0.123 (0.116, 0.130)
J	G - RGB - MD/PH	1/82 to 4/82	0.125 (0.115, 0.136)	0.150 (0.139, 0.163)	0.172 (0.159, 0.186)	0.190 (0.176, 0.206)	0.198 (0.182, 0.214)
		7/84 to 8/84	0.136	0.173	0.205	0.234	0.247
K	O/G - SAB - ND	2/81 to 10/81 (H_2 = 43.4%) (Oil = 31.0%) (%N = 0.63)	0.099 (0.093, 0.104)	0.111 (0.105, 0.177)	0.120 (0.114, 0.127)	0.128 (0.121, 0.136)	0.131 (0.123, 0.139)
		3/82 to 4/82 (H_2 = 46.6%) (Oil = 17%) (%N = 0.63)	0.112 (0.107, 0.117)	0.127 (0.124, 0.131)	0.140 (0.137, 0.143)	0.150 (0.147, 0.154)	0.157 (0.153, 0.161)
L	O/G - SAB - ND	2/81 to 10/81 First Part (Oil = 3%) (%N = 0.63)	0.051 (0.046, 0.057)	0.057 (0.051, 0.064)	0.062 (0.055, 0.069)	0.065 (0.058, 0.073)	0.068 (0.060, 0.076)
		Second Part (Oil - 7%) (%N = 0.63)	0.051 (0.049, 0.054)	0.058 (0.055, 0.061)	0.063 (0.059, 0.066)	0.067 (0.063, 0.071)	0.068 (0.064, 0.072)
		3/82 to 4/82 (Oil = 13%) (%N = 0.63)	0.086 (0.083, 0.089)	0.100 (0.097, 0.103)	0.111 (0.107, 0.115)	0.120 (0.116, 0.124)	0.124 (0.120, 0.128)

[a] See Table 4-2, footnote (a) for explanation of notation.

[b] The confidence interval for each predicted value is given in parenthesis.

stack oxygen level. A summary of the NO_x emissions reductions for each heater are presented in Table 4-6. The data indicate that on the average, a nine percent reduction in NO_x accompanies each one percent reduction in stack oxygen level. For example, if the average long term stack oxygen level of a heater was reduced from 5.5 percent O_2 to 2 percent O_2 using LEA control techniques, a 32 percent reduction in NO_x emissions would result.

4.2 LOW NO_x BURNERS

The following sections describe low NO_x burner technology (Section 4.2.1), applicability to fired heaters (Section 4.2.2) and NO_x emissions performance data (Section 4.2.3).

4.2.1 Technology Description

Low NO_x burners are designed to have lower NO_x emissions than conventional burners while providing equivalent heating characteristics. Due to the diversity of low-NO_x burner types, a general definition of low-NO_x burners is needed to encompass the many existing and new designs designated by burner vendors as low-NO_x burners. For the purposes of this report, a burner is classified as a low-NO_x burner if it meets any one of the following three criteria: (i) the burner is designated by the vendor as a low-NO_x burner, (ii) the burner is chosen by the user for the specific purpose of meeting a permit limit for NO_x emissions, or (iii) the burner has NO_x emissions equivalent to or less than those of burners classified as low-NO_x burners under criteria (i) or (ii), when operated under identical conditions.

The burners may differ in specific design features as well as in the physical principles responsible for their effectiveness. Low-NO_x burners can be designed to produce various types of flames (e.g., round, conical, or flat flames) or to burn various types of fuel (e.g., gas, oil, or gas/oil combinations). Other low-NO_x burners have been designed for specific applications (e.g., radiant wall low-NO_x burners and high intensity low-NO_x

TABLE 4-6. PERCENT REDUCTION OF NO_x EMISSION PER PERCENT DECREASE IN STACK OXYGEN LEVEL DUE TO LOW EXCESS AIR COMBUSTION MODIFICATION

Draft Type	Heater Code	$\Delta NO_x/\Delta O_2 \times 100\%$[a]
Natural Draft	A	10.1
	B	7.2
	C	13.8
	D	6.5
	E	12.0
	F	16.4
	G	8.2
	H	4.7
	I	4.4
	K	6.9
	L	6.7
Mechanical Draft	J	11.6
Overall Average		9.0

[a] $$\frac{\Delta NO_x}{\Delta O_2} = \frac{\left[[NO_x]_{baseline} - [NO_x]_y\right]}{[NO_x]_{baseline}} \Big/ \left[SOL_{baseline} - SOL_y\right]$$

where SOL = Stack Oxygen Level
baseline = 5.5% O_2
= 3% O_2 for natural draft heaters;
2% O_2 for mechanical draft heaters.
$[NO_x]$ = NO_x emission factor (lb/MMBtu)

burners).[13] Several types of low-NO_x burners applicable to fired heaters are commercially available. The most frequently used low-NO_x burners are staged-air burners, staged-fuel burners, and flue gas recirculation burners. These burner types are discussed below. Other low-NO_x burner types are available, including a design that employs a split flame to dissipate heat and lower peak flame temperature.

4.2.1.1 Staged Air Low-NO_x Burner--

The low-NO_x burner most commonly used with existing fired heaters employs staged air addition to the fuel stream (i.e., a staged-air burner). This design is shown in Figure 4-6. The primary combustion zone is operated under conditions of substoichiometric combustion air, which leads to a reducing atmosphere rich in hydrogen and carbon monoxide. These species act as reducing agents for any fuel NO_x and/or thermal NO_x formed in the primary combustion zone. Internal recirculation of some of the combustion products formed in the primary zone is induced by the use of recirculating tiles. This causes a reduction in the temperature of the primary zone and reduces thermal NO_x formation. Additional air is added to the primary zone exit gases in the secondary combustion zone to ensure complete combustion. The cooling effect of the staged air addition reduces the secondary combustion zone temperature, thereby limiting the formation of NO_x by the thermal NO_x mechanism. The net result of the staged air burner is a reduction in fuel NO_x formation and thermal NO_x formation due to the reducing atmosphere of the primary combustion zone and the lowered temperature of the secondary combustion zone, respectively.[11]

4.2.1.2 Staged Fuel Low NO_x Burner (SFB)--

Similar to the staged air and flue gas recirculation low-NO_x burners, the staged fuel low-NO_x burner also uses staged combustion to reduce NO_x emissions, but the staging principle is reversed. With this burner type, the fuel is added to the combustion air in staged increments such that the first combustion zone is operated at high excess air (i.e., fuel-lean) and the second is operated at low excess air (i.e., fuel-rich). Figure 4-7 shows an example of a staged-fuel low-NO_x burner.

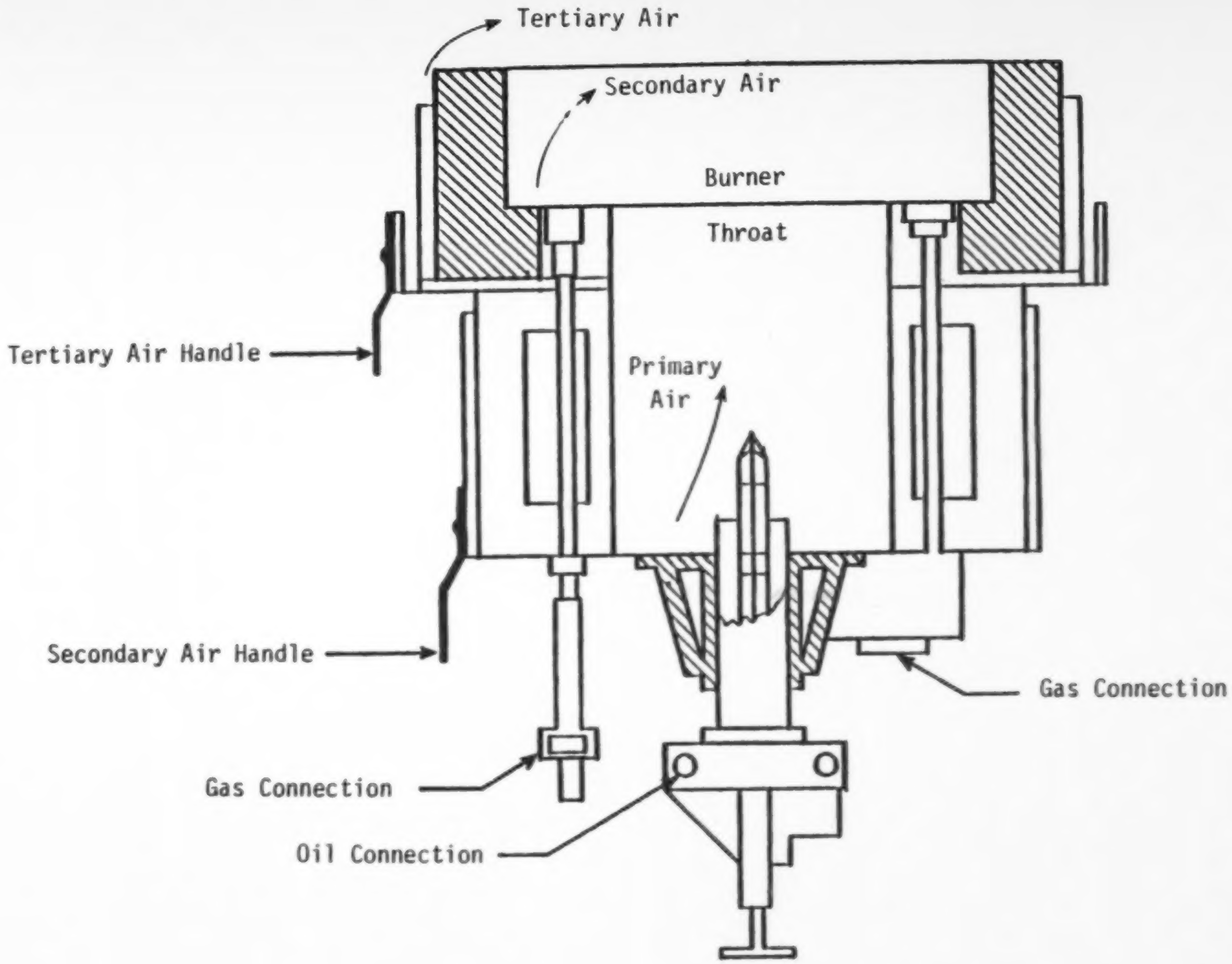
Tertiary Air
Secondary Air
Burner
Throat
Tertiary Air Handle
Primary
Air
Secondary Air Handle
Gas Connection
Gas Connection
Oil Connection

Figure 4-6. A staged air addition low-NO_x burner.[13]

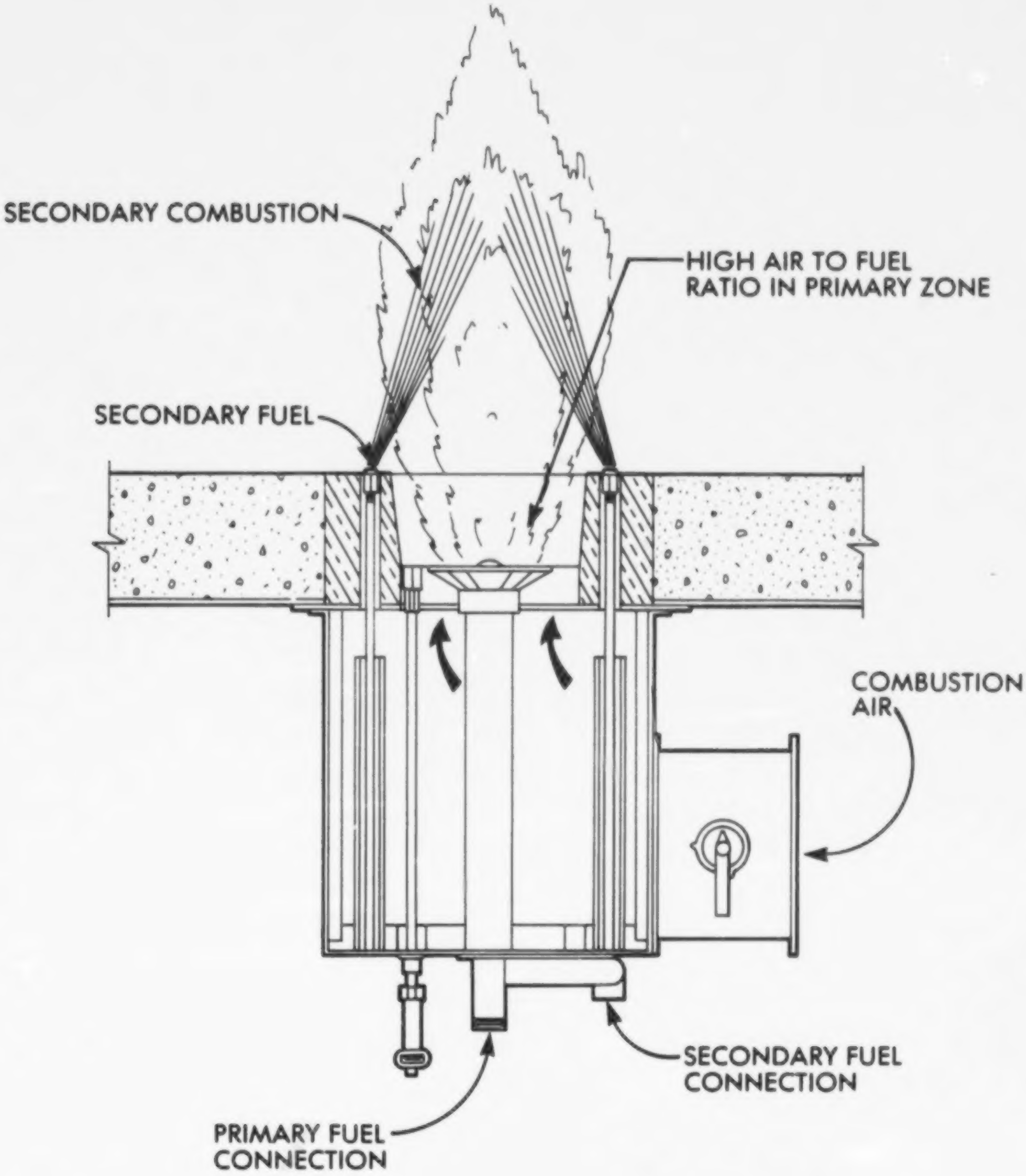
SECONDARY COMBUSTION
HIGH AIR TO FUEL RATIO IN PRIMARY ZONE
SECONDARY FUEL
COMBUSTION AIR
SECONDARY FUEL CONNECTION
PRIMARY FUEL CONNECTION

Figure 4-7. Staged-fuel low-NO_x burner.[15]

In the fuel-lean primary zone, the large quantity of combustion air reduces the peak flame temperature as the fuel combusts rapidly. The lower peak flame temperature reduces NO_x formation in the primary zone. In the fuel-rich secondary zone the remainder of the fuel is injected under pressure through nozzles positioned around the perimeter of the burner. The pressurized fuel entrains and rapidly mixes with the combustion gases from the primary zone. The entrained combustion gases reduce the partial pressure of oxygen in the secondary zone which decreases the availability of oxygen and reduces NO_x formation. Also, the H_2 and CO formed in the primary zone reduces in the secondary zone some of the NO_x formed in the primary zone. The peak flame temperature decreases reducing NO_x formation due to heat transfer between the primary and secondary zones and due to the recirculation of the primary zone combustion gases.[14]

The staged-fuel low-NO_x burner has several advantages; first, the improved fuel/air mixing due to the pressurized injection of the secondary zone fuel reduces the excess air operating level necessary to ensure complete combustion. The lower excess air reduces NO_x formation as well as improves heater efficiency. Also, for a given peak flame temperature, staged-fuel low-NO_x burners have a more compact flame than staged air low-NO_x burners.[14] One burner manufacturer reports that customers preferred staged-fuel low-NO_x burners because of flame pattern, low excess air and ease of operation.[16] This company has sold approximately 3,000 staged-fuel low-NO_x burners in fired heater applications in the last 2 years.[16] The staged fuel burners have been installed as wall, floor and roof mounted burners and have found use in the full range of process applications from crude heater to downstream conversion processes except for cracking units which generally use pre-mix burners.[17] The burner vendor reported that staged fuel burners were selected to meet NO_x emissions standards.[17] Another burner manufacturer has reported that it will have a marketable staged fuel low-NO_x burner by the end of Summer, 1985.[18] The company estimated that about 60 to 65 percent of their present sales are low-NO_x burners and expects that about 50 percent of their low-NO_x burner sales will be staged-fuel low-NO_x burners.[18]

Continuous NO_x monitoring data were not available for heaters with staged fuel burners. However, short-term performance test data were obtained for two heaters. One of these heaters is a feed preheater for a hydrotreating process which was retrofitted with staged-fuel burners. The heater emitted 0.08 lb/MMBtu NO_x during the performance test. NO_x emissions were reduced 50 percent from the level measured during a performance test for the same heater with conventional burners.[19]

The other heater with staged-fuel burners is a newly built steam hydrocarbon reformer. NO_x emissions were 0.18 lb/MMBtu during the performance test.[20,21]

4.2.1.3 Flue Gas Recirculation Low NO_x Burner (FGR)--

The flue gas recirculation burner relies on both flue gas recirculation and staged combustion to reduce NO_x emissions. A strong recirculation eddy in the burner throat tile draws combustion reaction products from the furnace and gasifies the fuel stream, thereby creating a NO_x-reducing atmosphere rich in hydrogen and carbon monoxide. The gasified stream leaves the burner and mixes with secondary air in the furnace for complete combustion.[22] A schematic diagram of this burner design is shown in Figure 4-8.

4.2.2 Applicability

In new heaters, low-NO_x burners may be used instead of conventional burners regardless of draft type, fuel type, flame type and other factors. Designs are available to accommodate natural and mechanical draft, combustion air preheat, gas and oil fuels, and various flame shapes. Special low-NO_x burner designs are available for firing low heating value fuels (high intensity low-NO_x burners) and for providing uniform radiant heat transfer from the furnace walls (radiant wall low-NO_x burners). The use of low-NO_x burners for a specific fired heater application may be limited only if the application has unusual process requirements or in some retrofitted heaters. The longer staged air low-NO_x burner flame length may cause flame impingement problems in retrofitted heaters.

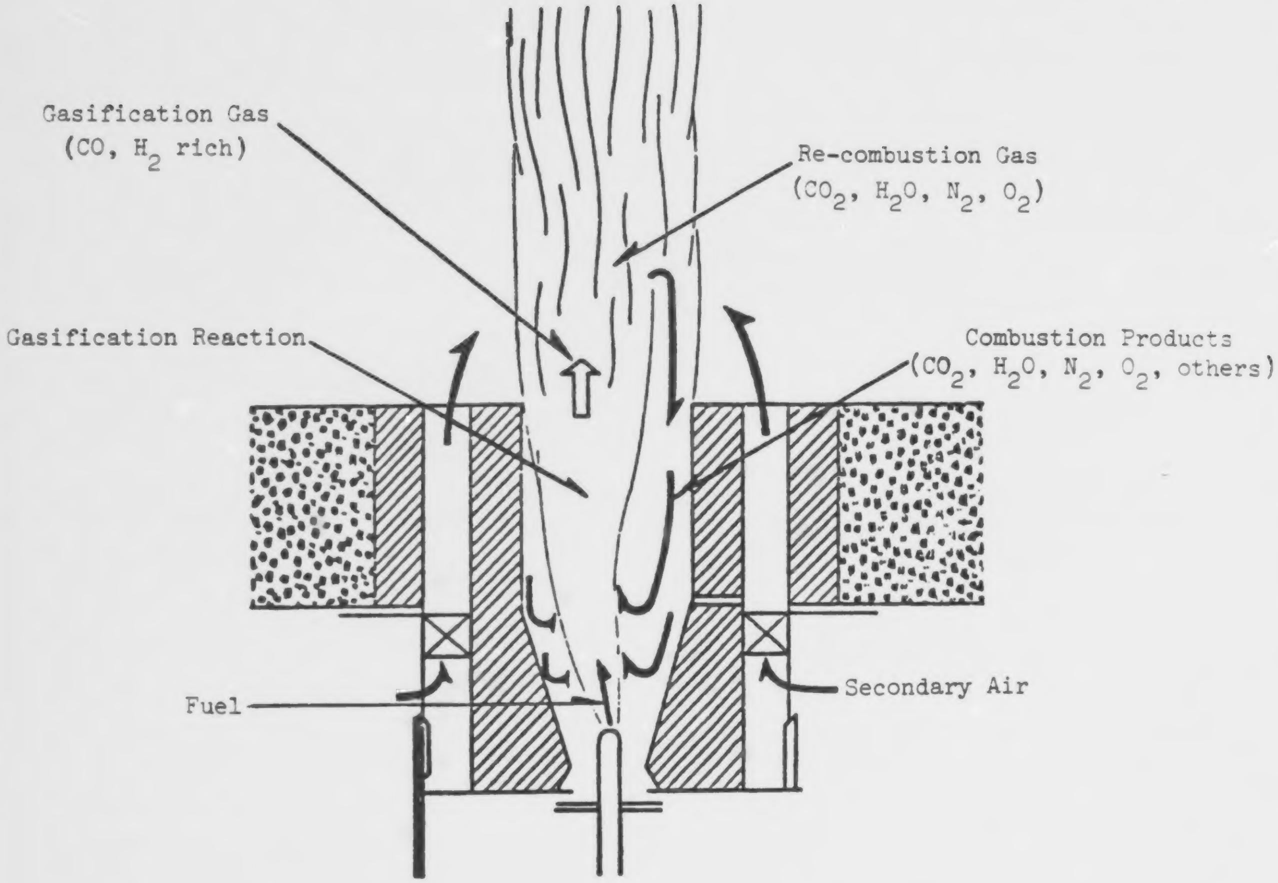
Gasification Gas
(CO, H_2 rich)
Re-combustion Gas
(CO_2, H_2O, N_2, O_2)
Gasification Reaction
Combustion Products
(CO_2, H_2O, N_2, O_2, others)
Fuel
Secondary Air

Figure 4-8. Cross-section of a self-recirculating gasification burner.[23]

Table 4-7 lists the petroleum refinery fired heater applications for which low-NO_x burner emissions data are available. The table is not intended to be a comprehensive list of all refinery heater low-NO_x burner applications, but is representative of the heater types that are compatible with the use of low-NO_x burners. The six heater applications shown account for approximately 86 percent of the fired heater energy used in a typical refinery. Much of the remaining fired heater energy is accounted for by other heater types that should be compatible with low-NO_x burners, based on a comparison of the process requirements in Table 4-4. This group includes the fired heaters associated with visbreaking, fluidized catalytic cracking, catalytic hydrocracking, catalytic reforming and hydrotreating.

Low-NO_x burner applications in the chemical industry are also very diverse. Table 4-8 lists the chemical industry fired heater applications that are currently using low-NO_x burners, as reported by members of the Chemical Manufacturer's Association (CMA).[24] The list includes both fired reactors and fired preheaters. Table 4-9 lists the fired heater applications reported by at least some CMA members to be incompatible with the use of low-NO_x burners. Some chemical industry processes requiring fired heaters are listed in both Tables 4-8 and 4-9, indicating uncertainty among some members of the CMA as to the applicability of low-NO_x burners to these overlapping processes. However, since other CMA members reported that low-NO_x burners are currently being used for these fired heater applications, low-NO_x burners are considered demonstrated in these cases. The only applications considered by some CMA members to be incompatible with low NO_x burners that have not been demonstrated as compatible with low-NO_x burners by other CMA memers are carbon disulfide, diphenylamine, and biphenyl. The reasons for their incompatibility with low-NO_x burners is not known. These three chemicals represent a small fraction of the energy supplied by fired heaters to the chemical industry.

4.2.3 Performance Data

Of the 12 heaters for which continuous NO_x monitoring data were obtained in this study, six were low to medium temperature heaters with

TABLE 4-7. PETROLEUM REFINERY PROCESSES FOR WHICH LOW-NO_X BURNER DATA ARE AVAILABLE

Heater Type	Estimated Percent of Fired Heater Capacity[a] (Energy Basis)
Crude heater	26
Naptha reformer	20
Vacuum column heater	15
Debutanizer bottoms reboiler	2
Hydrodesulfurization preheater	10
Coke heater	13
	86

[a] Values taken from Table 3-12.

TABLE 4-8. CHEMICAL INDUSTRY PROCESSES FOR WHICH LOW-NO_x BURNERS ARE REPORTED TO BE IN USE[24]

Ammonia (steam hydrocarbon reformers)
Olefins (ethylene pyrolysis furnaces)
Butadiene
Cumene
Xylene
Silicones
PVC and polymers
Agricultural chemicals
Isocyanate
PVC film
Ethylbenzene/styrene
Chlorinated organics/oxides
Biphenyl

TABLE 4-9. CHEMICAL INDUSTRY PROCESSES WITH WHICH LOW NO_x BURNERS ARE REPORTED TO BE INCOMPATIBLE[24]

Olefins (ethylene pyrolysis furnaces)[a]

Synthesis gas, methanol (steam hydrocarbon reformers)[a]

Butadiene[a]

Carbon disulfide

Aromatics (diphenylamine, biphenyl)

Polymers[a]

---

[a] This process is reported to be compatible with low-NO_x burners by at least one CMA member.

staged-air low-NO_x burners. The heater descriptions were previously presented in Table 4-2 (Heaters F thru I, K, and L). Continuous monitoring NO_x emissions data were not available for high temperature heaters with low-NO_x burners or for staged-fuel and FGR low-NO_x burners.

Long term data were not available showing a comparison of conventional burners and low-NO_x burners tested in the same commercial heater. These data would be ideal since operating design and maintenance differences would be minimized. However, in the absence of such data, the data between heaters of similar draft-type were compared to assess the performance of low-NO_x burners. The analysis did not account for such variables as leakage of air into the stack which would affect the stack oxygen level values. The NO_x emissions data were compared at two stack oxygen levels, baseline (5.5 percent O_2) and low excess air (3 percent for natural draft; 2 percent for mechanical draft). Table 4-10 presents the emission levels for each heater at the two stack oxygen levels as predicted by the models previously presented in Section 4.1.3.3. The comparison shows that the NO_x emission levels from the low-NO_x burner heaters with natural draft are not significantly different than the emission levels from the raw gas burner heaters with natural draft. Therefore, no conclusion about the performance of low-NO_x burners could be derived from the continuous monitoring data because the operating, design and maintenance differences between the heaters obscure the effect of the low-NO_x burners in reducing NO_x emissions. It was concluded that between-heater comparisons are not appropriate for determining the performance of low NO_x burners.

Thus, the only data available for evaluating the performance of low-NO_x burners are the test-scale data from burner vendors. Performance data supplied by vendors were used to evaluate the factors that affect NO_x emissions from low-NO_x burners. These factors include fuel type, degree of combustion air preheat, and excess air. In addition, the degree of burner combustion air or fuel staging affects NO_x emissions from low-NO_x burners.

The effects of fuel type and combustion air preheat temperature on NO_x emissions from low-NO_x and conventional burners are indicated in Figures 4-9 and 4-10. The curves shown are based on data obtained in a John Zink test furnace.[10] The following trends are indicated by the data:

TABLE 4-10. COMPARISON OF PREDICTED NO_x EMISSION FACTORS FOR LNB, RGB, AND PMB HEATERS

Heater Classification[a]	Heater Code	Stack Oxygen Level Baseline[b]	 Low Excess Air[c]
G-RGB-ND	A	0.113	0.085
	B	0.089	0.073
Classification Average		0.101	0.079
G-SAB-ND	F	0.105	0.077
	G	0.137	0.109
	H	0.112	0.100
	I	0.123	0.111
Classification Average		0.119	0.099
G-PMB-ND	C	0.147	0.094
	D	0.129	0.108
	E	0.103	0.073
Classification Average		0.126	0.092
O/G-SAB-ND	K	0.144	0.119
	L	0.087	0.072
Classification Average		0.116	0.096
G-RGB-MD/PH	J	0.223	0.131
Classification Average		0.223	0.131

[a] See Table 4-2, footnote (a) for explanation of notation.

[b] Baseline = 5.5% O_2.

[c] Low Excess Air = 3% O_2 for natural draft heaters;
2% O_2 for mechanical draft heaters.

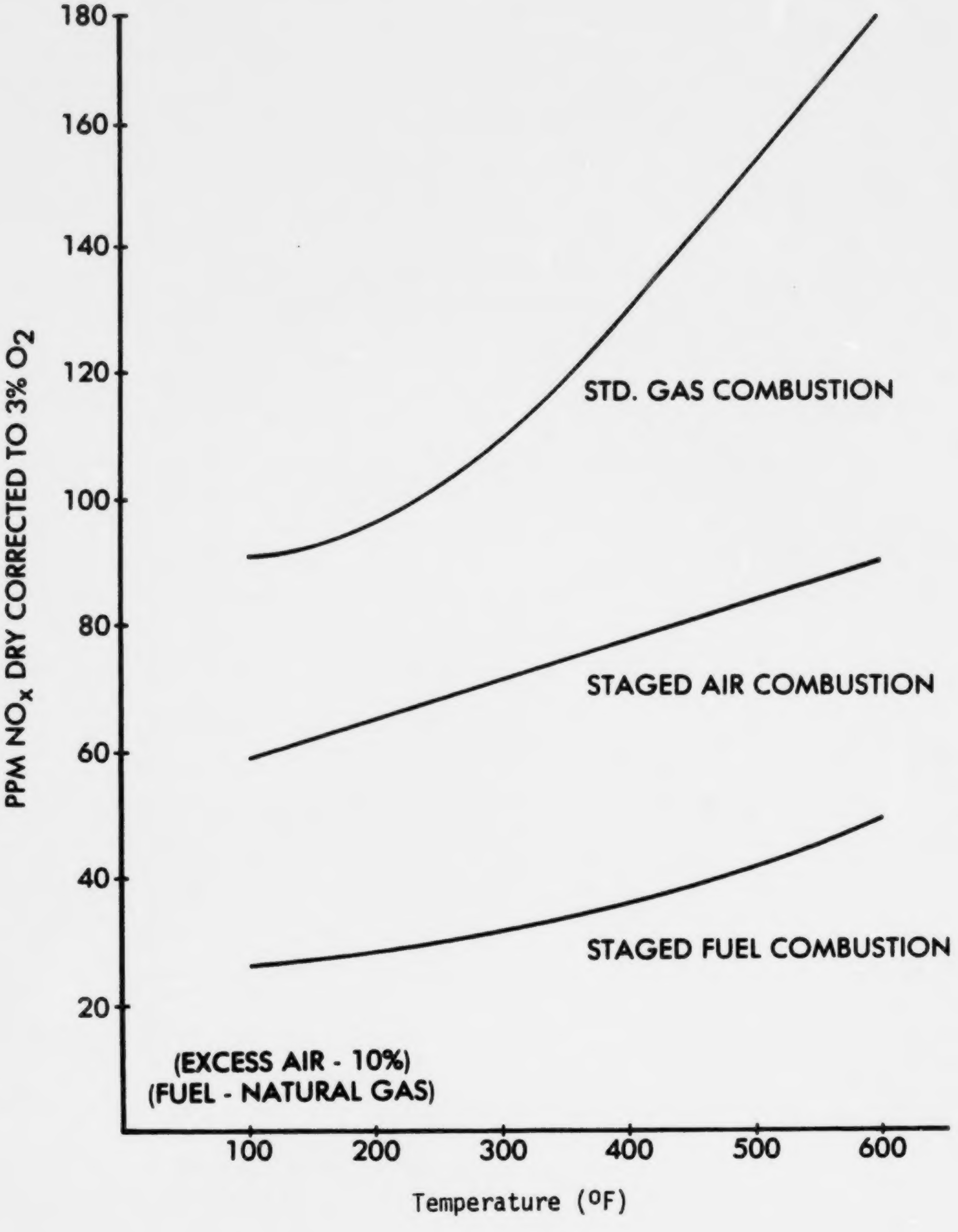

Figure 4-9. NO_x emissions as a function of combustion air preheat and burner types for a natural gas-fired heater.[25]

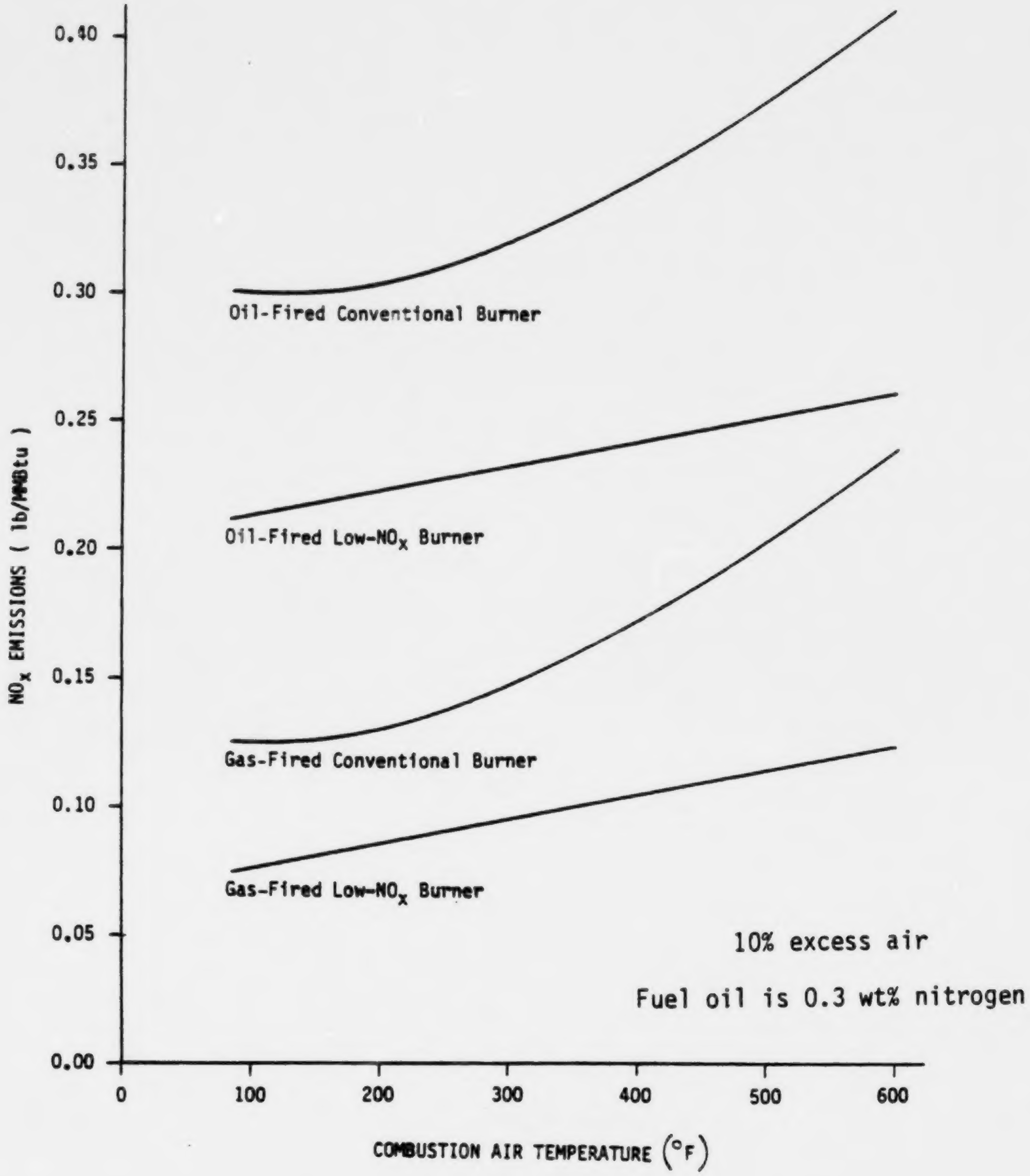

Figure 4-10. NO_x emissions as a function of combustion air preheat and fuel type on a natural draft heater.[13]

*Reproduced with permission from John Zink Services, Inc.

- For a given set of fuel, combustion air preheat, and excess air conditions, NO_x emissions are the highest from unstaged conventional burners and the lowest from staged-fuel low-NO_x burners. Under the test conditions corresponding to Figure 4-9, the magnitude of the emissions reductions associated with the use of staged-air low-NO_x burners ranged from 38 to 40 percent compared to conventional burners. NO_x reductions associated with the use of staged fuel low-NO_x burners ranged from 70 to 72 percent compared to conventional gas burners and from 45 to 55 percent compared to staged-air low-NO_x burners.

- Figure 4-10 shows that the effect of fuel type on NO_x emissions is about the same for both low-NO_x burners and conventional burners. NO_x emissions from burners firing oil with 0.3 weight percent nitrogen were consistently more than twice as high as those from comparable burners firing gas.

- The effect of 350°F combustion air preheat on NO_x emissions is to increase emissions by about 40 percent for both conventional burners and low-NO_x burners. Since preheated combustion air increases NO_x emissions for both low-NO_x and conventional burners and emissions from conventional burners are higher than NO_x emissions from low-NO_x burners, the magnitude of the NO_x emissions reduction due to low-NO_x burners, is greater with preheated combustion air than the magnitude of the NO_x emissions reduction due to LNB with ambient combustion air.

- Above combustion air temperatures of 350 to 400°F, NO_x emissions increase more rapidly for conventional burners than for both staged air and staged fuel low-NO_x burners.

NO_x reductions from heaters with low-NO_x burners are affected by the overall excess air. The results in Table 4-6 indicate that when an LEA control system is used with low-NO_x burners, NO_x reduction due to LEA is the same as when an LEA control system is used with conventional burners. Therefore LEA would reduce NO_x emissions by approximately 9 percent per 1 percent decrease in stack oxygen for both low-NO_x and conventional burners.

The degree of burner air staging or fuel staging employed on low-NO_x burners can have a substantial effect on NO_x emissions. Under optimal operating conditions for staged-air burners the combustion air should be distributed between the primary and secondary combustion zones so that NO_x emissions are minimized. The optimal operating condition is determined experimentally by increasing the degree of staging until a minimum in NO_x emissions is reached while maintaining the desired flame quality.[26]

For staged-fuel burners, the fuel is typically distributed from about 40 to 60 percent to the primary zone and 60 to 40 percent to the secondary zone. Also the air is distributed with about 90 percent to the primary zone and 10 percent to the secondary zone.[27] When no combustion air staging or fuel staging is employed, NO_x emissions from low-NO_x burners are identical to those of conventional burners.

4.3 STAGED COMBUSTION AIR (AIR LANCES)

Staged combustion air (SCA) is a combustion modification technique that can be applied alone, or concurrently with LEA and/or low-NO_x burners. The following sections describe SCA technology (Section 4.3.1), applicability to fired heaters (Section 4.3.2) and NO_x emissions performance data (Section 4.3.3).

4.3.1 Technology Description

The SCA technique for reducing NO_x emissions combusts the fuel in two zones while the overall air/fuel ratio is unchanged. The first or primary combustion zone is fuel-rich, and partial combustion occurs with substoichiometric combustion air. Combustion is completed in an air-rich secondary zone by adding air above the top row of burners.[28]

The secondary air is most commonly supplied by one or more air lances. A schematic diagram of a staged combustion system using air lances to inject secondary air to the flame is shown in Figure 4-11. The air lances may be natural draft or forced draft. When the heater draft draws insufficient air through natural draft air lances for complete combustion, forced draft air lances are necessary.[29] Typically, four lances spaced 90° apart are inserted through the furnace floor around each burner. The end of the lances can be angled 45° inward to improve fuel/air mixing across the flame.[26,30,31,32] The installation of the lances requires no down-time, since the lances may be installed with the heater on-line.[33] When the lances are first installed, the ratio of primary to secondary air and the height of the lances above the gas tips are optimized with respect to NO_x emissions since these two parameters vary for individual heaters.[31,32] Also, the residence time of the secondary zone is adjusted to insure complete combustion. The secondary zone residence time is usually equal to or greater than that of the primary zone.

SCA reduces NO_x emissions in several ways. In the primary zone, fuel NO_x formation is limited by the reducing atmosphere created by substoichiometric combustion. The partial combustion also lowers peak flame temperatures and thus reduces thermal NO_x formation. The gases from the primary zone are cooled by flame radiation heat transfer when the secondary air is added. This reduces peak temperatures and suppresses thermal NO_x formation in the secondary zone.

4.3.2 Applicability of SCA

The applicability of SCA to fired heaters has been demonstrated in a long term EPA test and on a commercial basis by at least one refinery in California. So far SCA has been used only in retrofit applications, but it could also be used on new fired heaters. In the EPA study, a full-scale, natural gas-fired, vertical crude heater with natural draft was retrofitted with forced draft air lances and operated for 30 days.[32] The same heater was also retrofitted with natural draft air lances and operated for 15 days.[31]

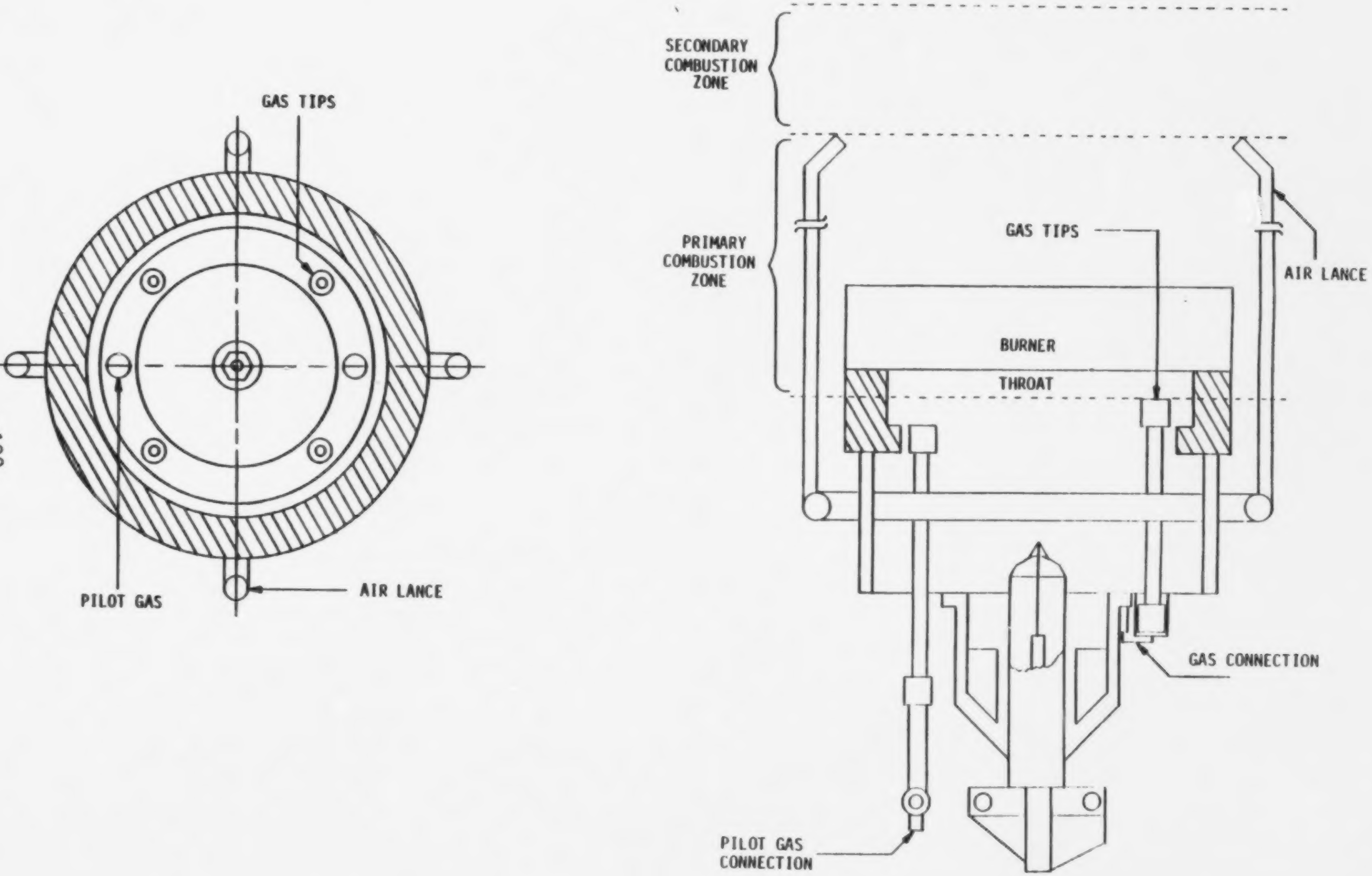
GAS TIPS
PILOT GAS
AIR LANCE
SECONDARY COMBUSTION ZONE
PRIMARY COMBUSTION ZONE
GAS TIPS
AIR LANCE
BURNER
THROAT
GAS CONNECTION
PILOT GAS CONNECTION

Figure 4-11. Staged combustion air lances installed on a conventional raw gas burner.

Commercially, the California refinery has been successfully operating three low temperature heaters retrofitted with natural draft lances. The heaters have been operating since May of 1983 with no problems.[24]

Although SCA is potentially applicable to many fired heater types, its use may be restricted by several limitations. As the degree of staging is increased, the flame quality and temperature decrease, and the uniformity of the heat flux provided by the flame is impaired. In heaters where the process fluid flow may be seriously affected by variations from the design heat flux distribution, staged air lances may not be applicable. For example, reforming heaters and vacuum heaters often have process fluids of more than one phase or at high temperature which require a constant heat flux distribution. Other heater types, such as crude heaters have been demonstrated to tolerate changes in heat flux and temperature more readily.[35] Other limitations include the possible corrosive environment due to staged combustion within the heater leading to frequent replacement of air lances. A larger flame zone would be required in some heaters to accommodate the lengthened flame associated with staged combustion.[36]

Therefore, although staged air lances have been retrofitted on at least three refinery heaters, their long-term applicability to fired heater service has not yet been demonstrated on a wide variety of heater types to the extent that the applicability of LEA and low-NO_x burners has been demonstrated.

4.3.3 Performance Data

The effectiveness of staged combustion air lances in reducing NO_x emissions from fired heaters is based on the NO_x reduction achieved from a heater that was tested with natural draft air lances and forced draft air lances. The heater used for both the natural and forced draft air lance tests was a gas-fired, natural draft heater with conventional raw gas burners. In addition to the forced and natural draft air lances tests, a baseline test was also performed on the heater. The heater has a rated capacity of 55 MMBtu/hr and has six DBA-22 John Zink burners.

A summary of the average stack oxygen level, fuel firing rate and NO_x emissions from the continuous monitoring data is presented in Table 4-11. The heater operated in the range of 3 to 5 percent oxygen during the three test periods. The percent combustion air staging was set at about 30 percent for both the natural draft and forced draft tests. Although the fuel firing rate was slightly different for each test, it was approximately 70 percent of the rated heater capacity throughout the test program. The NO_x reduction is evaluated by mathematically modeling the relationship between NO_x emissions and stack oxygen level based on the long term continuous NO_x and O_2 monitoring data from the tests. The mathematical model to which the data was fit for each of the tests correlates the relationship of NO_x emissions to stack oxygen level and heater load. The model terms for the degree of oil-firing and fuel gas hydrogen content were not included in the model because the heater was 100 percent gas fired and the fuel gas hydrogen content was not measured on a regular basis. The model and its application to continuous NO_x and O_2 emissions data is described in more detail in Appendix C. The model coefficients and coefficient of determination for each test data set are presented in Table 4-12.

For each test data set, the NO_x emission level is predicted at variable stack oxygen levels while the heater load is held constant. The NO_x emission levels predicted at 2 percent, 3 percent, 4 percent, 5 percent and 5.5 percent oxygen are shown in Table 4-12. The heater load was set at the level corresponding to the test conditions.

The effectiveness of the natural and forced draft air lances was evaluated by comparing their NO_x emission levels to the baseline test levels at fixed stack oxygen level. The predicted emission levels with and without staged air lances are compared at 3 percent and 5.5 percent oxygen and are shown in Table 4-13. The comparison shows that at a fixed oxygen level, natural draft air lances reduce NO_x emissions by 10-20 percent and forced draft air lances reduce NO_x emissions by 50-60 percent relative to emissions from the heater without staged air lances. Forced draft air lances reduced NO_x emission by 30-50 percent more than natural draft air lances. The percent NO_x reduction are given as ranges because they vary with the stack oxygen level considered for the comparison.

TABLE 4-11. SUMMARY OF STAGED COMBUSTION AIR (AIR LANCES) DATA IN THE CONTINUOUS MONITORING NO_x EMISSIONS DATA BASE

Data Set	Test Period	Parameter	Number of Data Points[b]	Average	Range	Standard Deviation
Baseline (No Air Lance)	3/14/82 - 3/16/83	Stack O_2 (%)	95	3.65	0.70 - 5.40	0.96
		Fuel Firing Rate[a] (MMBtu/hr)	-	45.2	-	-
		NO_x Emissions (lb/MMBtu)	95	0.135	0.067 - 0.149	0.012
Forced Draft Air Lance	5/1/81 - 6/2/81	Stack O_2 (%)	2941	2.90	0.10 - 10.80	1.54
		Fuel Firing Rate (MMBtu/hr)	3077	36.32	36.27 - 38.15	0.30
		NO_x Emissions (lb/MMBtu)	2941	0.052	0.003 - 0.133	0.021
Natural Draft Air Lance	3/16/83 - 3/31/83	Stack O_2 (%)	1390	3.43	0.30 - 6.40	0.96
		Fuel Firing Rate[a] (MMBtu/hr)	-	45.2	-	-
		NO_x Emissions (lb/MMBtu)	1390	0.106	0.016 - 0.198	0.029

---

[a] Fuel firing rate was constant throughout test.

[b] Number of 15 minute averages.

TABLE 4-12. MODEL COEFFICIENTS AND VARIATION OF NO_x EMISSIONS WITH STACK OXYGEN FOR HEATERS WITH STAGED AIR COMBUSTION (AIR LANCES) IN THE CONTINUOUS MONITORING NO_x EMISSIONS DATA BASE.

Data Set	Model Coefficients C_1	C_3	Coefficient of Determination	Predicted NO_x Emissions at Tested Heater Load and Varying Stack Oxygen Levels (lb/MMBtu)[a] $2\%\ O_2$	$3\%\ O_2$	$4\%\ O_2$	$5\%\ O_2$	$5.5\%\ O_2$
Baseline (No Air Lance)	0.45	0.36	0.93	0.110 (0.080,0.140)	0.127 (0.097,0.157)	0.141 (0.111,0.171)	0.152 (0.122,0.182)	0.158 (0.128,0.188)
Forced Draft Air Lances	0.51	0.64	0.81	0.042 (0.002,0.082)	0.054 (0.015,0.093)	0.065 (0.026,0.104)	0.075 (0.037,0.113)	0.080 (0.042,0.118)
Natural Draft Air Lances	0.27	0.26	0.78	0.098 (0.069,0.127)	0.109 (0.080,0.138)	0.117 (0.088,0.146)	0.124 (0.095,0.153)	0.127 (0.098,0.156)

[a] The values were calculated using three significant digits on the coefficients.

TABLE 4-13. EFFECTIVENESS OF STAGED AIR LANCES IN REDUCING NO_x EMISSIONS FROM FIRED HEATERS

Date Set	Predicted NO_x Emissions At Tested Heater Load (lb.MMBtu) 5.5%	(lb/MMBtu) 3%	Percent NO_x Reduction Associated With Staged Air Lances 5.5%	3%
Baseline (No Air Lance)	0.158	0.127	-	-
Forced Draft Air Lance	0.080	0.080	57	49
Natural Draft Air Lance	0.127	0.109	20	14

4.4 FLUE GAS RECIRCULATION (FGR)

Flue gas recirculation (FGR) is a combustion modification technology which has been applied to fired heaters on a more limited scale than low-NO_x burners, LEA, and SCA. FGR and the available NO_x emissions data are discussed briefly in the following paragraphs.

FGR is a NO_x emissions reduction technique based on recycling 15 to 30 percent of the essentially inert products of combustion (flue gas) to the primary combustion zone. A diagram of a flue gas recirculation system is shown in Figure 4-12. The recirculation of flue gas dilutes the combustion reactants, reduces the peak flame temperature, and reduces the local oxygen concentrations, thereby inhibiting thermal NO_x formation. FGR is believed to have only a small effect on fuel NO_x formation.[37]

Flue gas recirculation has been used on only a few fired heaters, and several inherent drawbacks will limit its use in the future. The most important of these is that the technology is usually not cost-effective because of the increased energy costs associated with transporting and reheating the recirculated flue gas.[37] Flue gas recirculation requires a relatively large capital investment because of the need for high-temperature fans and ductwork. Furthermore, it may not be applicable to all types of fired heaters. Its low flame temperature and susceptibility to flame instability limits its usage in high temperature applications. In addition, FGR can only be used on forced draft heaters because of the need to recirculate the flue gas.[37]

Since FGR is believed to have only a small effect on fuel NO_x formation, FGR may not be as effective on oil-fired heaters, as on gas-fired heaters. Data are not available to document the percent NO_x emission reduction achievable with FGR. The only NO_x emissions data available on a fired heater using flue gas recirculation consist of five spot measurements on a 100 MM Btu/hr crude heater with mechanical draft, ambient combustion air, and unknown burner type. The average operating conditions of the heater were 74 percent load, 1150°F flue gas recirculation temperature, and 14.0 percent stack oxygen. The average NO_x emissions from the heater were 0.18 $lb/10^6$ Btu.[37]

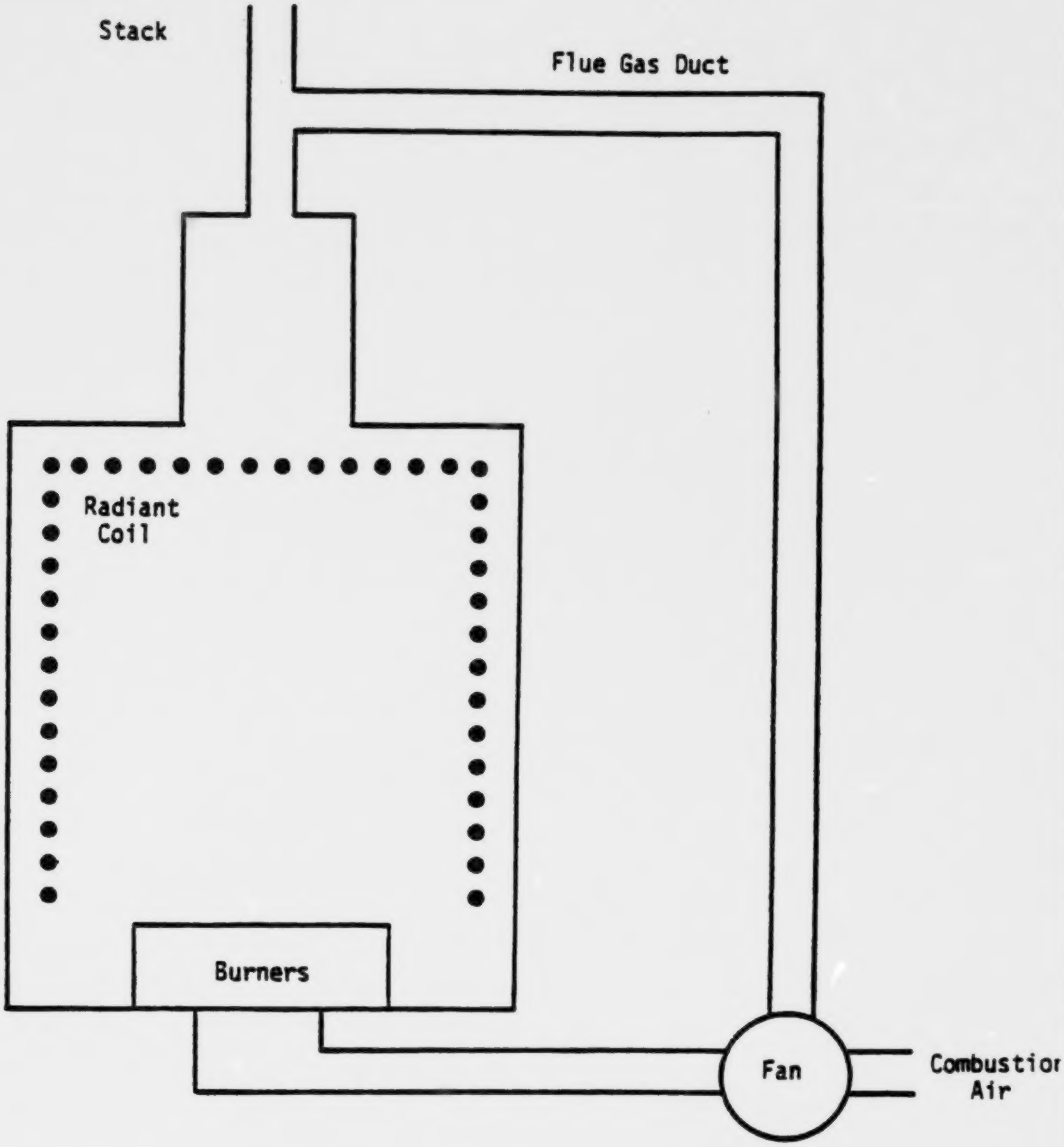
Stack
Flue Gas Duct
Radiant Coil
Burners
Fan
Combustio
Air

Figure 4-12. Flue gas recirculation on a mechanical draft heater.[38]

4.5 FLUE GAS TREATMENT TECHNIQUES

4.5.1 Selective Non-Catalytic Reduction(SNCR)

Selective non-catalytic reduction (SNCR), sometimes referred to under the trade name Thermal De-NO_x, relies on the homogeneous gas phase reduction of NO_x by ammonia (NH_3). The fired heater flue gas is injected with ammonia at sufficiently high temperatures to enable the ammonia to reduce NO_x to nitrogen and water. At a mole ratio of 1.5 moles NH_3 per mole NO_x, over 40 percent of the NO_x can be reduced if the reaction takes place between 927° to 982°C (1700 to 1800°F). Outside the temperature range of 900° to 1093°C (1650 to 2000°F), less than 10 percent of the NO_x in the flue gas can be reduced.[40]

The SNCR process is applicable to most new fired heaters and can be used in conjunction with combustion modifications. The primary drawbacks limiting its practical application are the high cost of the process and the narrow temperature window required for efficient operation. Capital equipment costs of SNCR are about an order of magnitude more than those for combustion modification techniques, and ammonia and maintenance costs are substantial as well.

Selective non-catalytic reduction has been installed on several refinery fired heaters in California.[41] The NO_x reduction efficiency of the individual units depend on several factors including flue gas temperature, residence time at that temperature, initial NO_x concentration, NH_3/NO_x mole ratio, and degree of flue gas/ammonia mixing. In general, NO_x emissions reductions ranging from 35 to 70 percent have been achieved, with 80 percent reduction being an approximate upper bound.[42] Experience has shown that SNCR systems are very sensitive to conditions of low load and variable load. The ability of SNCR to reduce NO_x emissions becomes almost negligible when the heater load drops below 50 percent, because the temperature window required for efficient operation is not reached. Also, since SNCR performance is sensitive to the residence time of the NO_x/NH_3 mixture in the temperature window, significant load changes can decrease NO_x reduction capabilities considerably. Another disadvantage of SNCR systems is high ammonia carryover in the flue gas because of the relatively inefficient use of ammonia in the reduction process.[40]

4.5.2 Selective Catalytic Reduction (SCR)

Selective catalytic reduction (SCR) makes use of the selective reduction of NO_x by ammonia in the presence of a catalyst. A diagram of a selective catalytic reduction unit is shown in Figure 4-13. The fired heater flue gas is injected with an ammonia-containing gas stream, and the entire gas mixture is sent through the catalyst bed. The NO_x is reduced to nitrogen and steam by the ammonia. At a mole ratio of 1 mole NH_3 to 1 mole NO_x, about 90 percent of the NO_x can be reduced.[43]

The additional pressure drop due to the catalyst bed requires that the system include a fan. Therefore, an SCR system is applicable to most new mechanical draft fired heaters, although for retrofitted heaters a fan or additional fan capacity will be required. An SCR system can be used in conjunction with combustion modifications. Unlike SNCR, the performance of SCR does not vary with heater load, and ammonia carryover is small. One potential disadvantage of SCR systems is that they may not be applicable to oil-fired heaters due to problems with residual oil mist carryover and catalyst plugging. Other drawbacks limiting its practical application are high catalyst cost and the extensive ductwork that is required for installation.[43]

Selective catalytic reduction has been installed on at least nine refinery fired heaters in California.[41] New SRC systems on fired heaters are expected to be limited to NO_x non-attainment areas. One fired heater with an SCR unit has reported a NO_x emissions reduction of 90 percent and the SCR unit requires minimal operator attention.[43]

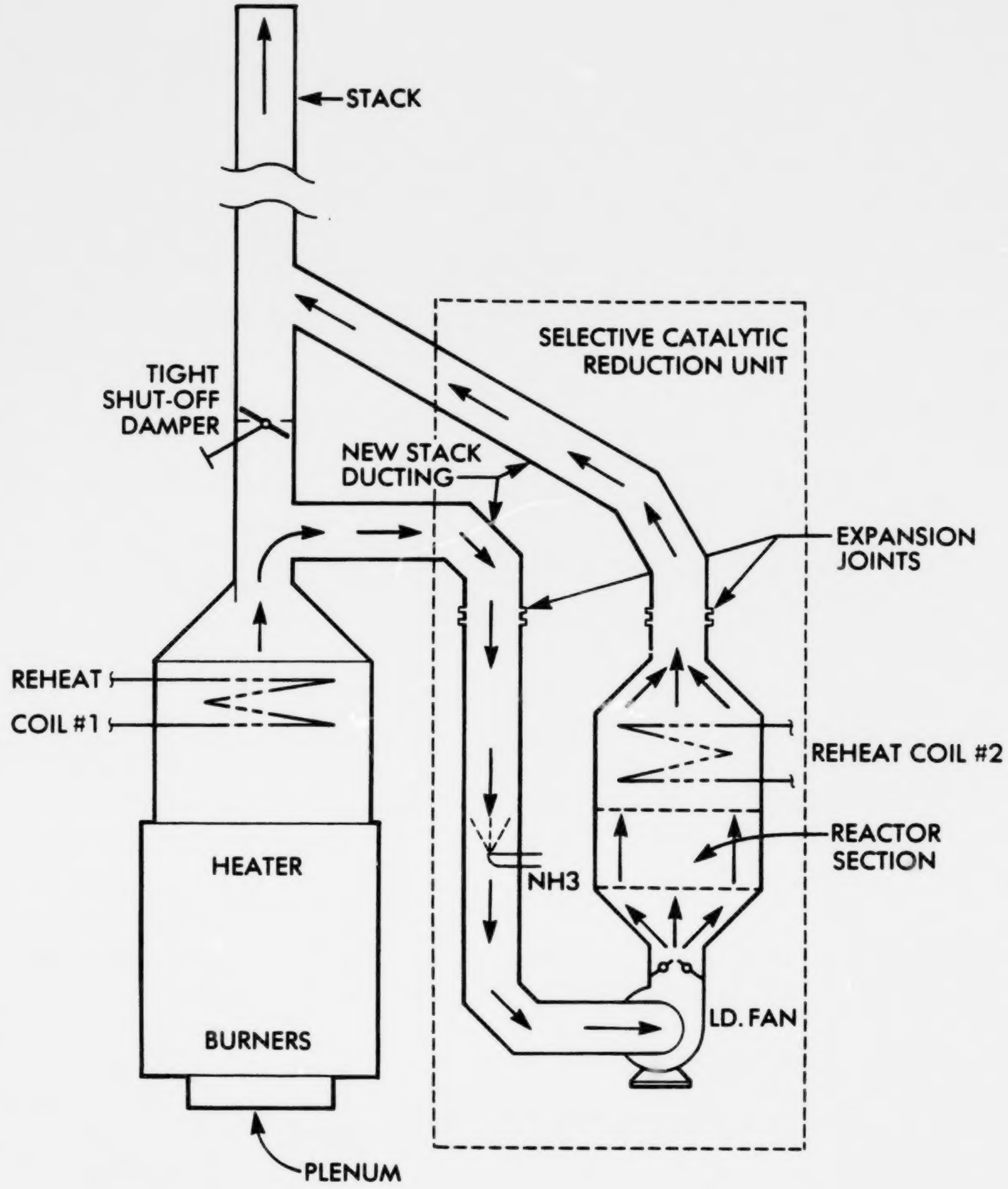
STACK
SELECTIVE CATALYTIC REDUCTION UNIT
TIGHT SHUT-OFF DAMPER
NEW STACK DUCTING
EXPANSION JOINTS
REHEAT COIL #1
REHEAT COIL #2
REACTOR SECTION
HEATER
NH3
LD. FAN
BURNERS
PLENUM

Figure 4-13. A selective catalytic unit applied to a mechanical draft fired heater.[44]

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SECTION 5
COST ANALYSIS

This section presents cost estimates for controlling NO_x emissions from fired heaters. The NO_x emissions control technologies which are evaluated are low excess air (LEA) control and staged-air low-NO_x burners. The cost of continuous NO_x emissions monitoring is also evaluated as an option to validate NO_x emissions levels.

Costs of the major equipment needed for the control technologies are determined from vendor quotes and data supplied by users of fired heaters. All cost estimates are updated to May 1985 dollars using the Chemical Engineering plant cost index.[1] Capital and annualized costs for LEA control, low-NO_x burners control and continuous NO_x emissions monitoring are presented in Sections 5.1, 5.2, and 5.3, respectively. A summary of the control costs is presented in Section 5.4.

5.1 LEA CONTROL COSTS

LEA control costs include the capital and annualized costs of installing the LEA control system and a fuel credit benefit due to low excess air operation. LEA control costs are discussed in Section 5.1.1 and LEA fuel credits are discussed in Section 5.1.2.

5.1.1 LEA Control Costs

The cost of installing LEA controls on a new fired heater depends on the complexity of the system being considered. A survey of LEA system vendors[2,3,4] indicates that the installed capital cost of LEA control systems ranges from approximately $7,000 to $150,000.

The LEA control system considered in this cost analysis consists primarily of an insitu O_2 analyzer, a damper positioner, and a microprocessor (i.e., control unit). This type of system was illustrated in

Figures 4-2 and 4-3 for natural draft and mechanical draft heaters, respectively. Other, more sophisticated LEA systems might include feedforward fuel/air control and/or CO monitoring. The system shown in Figures 4-2 and 4-3 is chosen for the cost analysis because it is considered to be a representative LEA control system that has been effectively demonstrated on fired heaters. All cost estimates for LEA control systems presented in this analysis assume that conventional fired heater controls such as those shown in Figure 4-1 are in place under baseline conditions. The costs of LEA control presented in this chapter represent incremental costs relative to the costs of conventional fired heater controls.

The total installed capital cost of the LEA control system considered in this analysis is estimated to be $36,300. A breakdown of the costs by component of the LEA system is presented in Table 5-1. This cost is independent of heater size, draft type, and combustion air preheat since these factors do not significantly affect the capital cost of the LEA system.

Annualized costs for the LEA control system considered in this analysis consist of capital recovery and the annual operating and maintenance costs. Most of the operating and maintenance costs of the system are associated with the O_2 analyzer. Annualized capital costs for the LEA control system are calculated assuming a 10-year equipment lifetime and a 10 percent annual rate of return (capital recovery factor = 0.163). As shown in Table 5-1, the total annualized cost of the LEA system is estimated to be $11,000/yr.

5.1.2 LEA Fuel Credits

As discussed previously in Section 4.1.1, LEA control systems increase heater efficiency by reducing the amount of fuel necessary to provide the required heat flux. Estimated annual cost savings associated with the fuel savings under LEA control are shown in Table 5-2. These cost savings depend on both heater size and draft type. Fuel use reductions under LEA control are estimated assuming a 0.5 percent increase in heater efficiency for each

TABLE 5-1. CAPITAL AND ANNUALIZED COSTS OF LEA CONTROL

Capital Cost Component	Capital Cost[a]
I. Capital Costs	
1. Equipment Costs	
a) Microprocessor[6]	$16,000
b) Power Damper Positioner[7]	$ 5,700
c) Insitu Oxygen Monitor	$ 2,500
TOTAL EQUIPMENT COST	$24,200
2. Installation Costs	$12,100
(@ 50 percent of equipment costs)[8]	
TOTAL INSTALLED CAPITAL COST	$36,300
II. Annualized Costs	
1. Direct Operating Costs	
a) Routine operating and maintenance costs of oxygen analyzer[b]	$ 4,200/yr
2. Capital Recovery Costs	
@ 10% rate of return, 10-year equipment lifetime (CRF = 0.163)[b]	$ 5,900/yr
TOTAL ANNUALIZED COSTS	$11,000/yr

[a] May 1985 dollars.

[b] Capital recovery factor (CRF) = $i(1 + i)^N/[(1 + i)^N - 1]$

where: i = fractional annual rate of return
N = equipment lifetime in years

TABLE 5-2. ANNUAL COST SAVINGS DUE TO LEA FUEL SAVINGS

Draft/ Preheat Type	Baseline Stack Oxygen Level (% O_2)	LEA Stack Oxygen Level (% O_2)	Annual Fuel[a,b] Savings (10^9 Btu/yr)	Annual Cost[b,c] Savings (10^3 \$/yr)
Natural Draft	5.5	3.0	0.210 x S	0.745 x S
Mechanical Draft/ Ambient	5.5	2.0	0.199 x S	0.707 x S
Mechanical Draft/ Preheat	5.5	2.0	0.171 x S	0.605 x S

[a] Annual fuel savings are based on 8,400 operating hours per year and the following baseline heater efficiencies: ND (70%); MD/AMB (85%); MD/PH (92%).

[b] S = heater size, MMBtu/hr (absorbed duty).

[c] May 1985 dollars.

1 percent reduction in stack oxygen level and the following baseline heater efficiencies: ND (70 percent); MD/AMB (85 percent); and MD/PH (92 percent).[5] Fuel gas is assigned a value of \$3.50/MM Btu.[9]

5.2 LOW-NO_x BURNERS CONTROL COSTS

Capital and annualized costs of low-NO_x burners control include the incremental costs of low-NO_x burners relative to conventional burners. The incremental cost of low-NO_x burners relative to conventional burners depends on heater size (MMBtu/hr) and number of burners per heater. Since the number of burners varies with the size and application of fired heaters, the cost of burners is estimated as a fraction of the total equipment cost of a heater. For the purpose of this analysis, incremental low-NO_x burners capital cost estimates were based on the following assumptions:

(1) the capital equipment cost of conventional burners represent 3 percent of the total equipment cost of a new fired heater;

(2) the total equipment cost of a new fired heater is a function of heater size given by the approximate relation:

$$C = 172.86 + 12.57 \times S$$

where C = heater equipment cost, (\$$10^3$, May 1985)

S = heater size, MMBtu/hr;

(3) low-NO_x burners cost approximately 25 percent more than conventional burners.

(4) heater and burner installation costs are 35 percent of the corresponding equipment costs.

Assumptions (1), (3), and (4) are based on information contained in Reference 21. The equation shown in Assumption (2) is based on a linear regression model of fired heater cost data contained in Reference 21.

Combining Assumptions (1) through (4) gives the equation shown in Table 5-3 for the incremental installed capital cost of low NO_x burners, relative to the cost of conventional burners. The annualized incremental cost of low-NO_x burners shown in Table 5-3 consists solely of capital recovery of low-NO_x burners. The capital recovery factor for low-NO_x

TABLE 5-3. INCREMENTAL CAPITAL AND ANNUALIZED COSTS OF LOW-NO_x BURNERS

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1. Incremental Installed Capital Cost of Low-NO_x Burners

$C = 1.75 + 0.127 \times S$

where: C = incremental installed capital cost of LNB, relative to conventional burners (10^3\$)
S = heater size (MM Btu/hr)

2. Incremental Annualized Cost of Low-NO_x Burners

$A = 0.285 + 0.0207$

where: A = incremental installed capital cost of LNB, relative to conventional burners (10^3\$)
S = heater size (MM Btu/hr)

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[a] May 1985 dollars.

burners was calculated assuming a burner lifetime of 10 years and a 10-percent annual rate of return (capital recovery factor = 0.163).

5.3 NO_x MONITORING COSTS

When verification of NO_x emissions levels achieved by the control technologies is desirable, continuous NO_x emissions monitors can be installed. Tables 5-4 and 5-5 summarize the capital and annualized costs of continuous NO_x monitoring for fired heaters. The capital costs shown in Table 5-3 include a NO_x analyzer, an O_2 analyzer, and the additional equipment necessary to perform continuous NO_x monitoring. The following equipment items are specifically included in the capital cost analysis:

- extractive-type chemiluminescent NO_x analyzer;
- O_2 analyzer;
- stainless-steel sample probe;
- 100 feet of heated sample line;
- heated sample gas conditioning unit;
- temperature controller;
- bypass pump;
- strip chart recorder;
- environmentally-controlled trailer or cabinet to house the monitoring equipment; and
- sample probe backflush unit.

The total installed capital cost of the NO_x monitoring system, including an initial performance specification test, is estimated to be $43,600.

Annualized costs shown in Table 5-5 for a continuous NO_x monitoring system for fired heaters consist of capital recovery, annual operating and maintenance costs, and a semi-annual relative accuracy test. The annualized cost is estimated to be approximately $42,080/yr.

TABLE 5-4. CAPITAL COST OF A CONTINUOUS NO_x MONITORING SYSTEM APPLICABLE TO FIRED HEATERS

Capital Cost Component	Capital Cost[a]
1. Equipment Costs	
a) extractive chemiluminescent NO_x analyzer[10,11,12,13]	$ 7,420
b) extractive O_2 analyzer[10,14,15]	$ 3,910
c) stainless-steel sample probe[10,11]	$ 960
d) 100 ft. of heated sample line[10,11]	$ 1,440
e) heated sample gas conditioning unit[11,13]	$ 3,580
f) temperature controller[10,11]	$ 860
g) bypass pump[10,11]	$ 280
h) strip chart recorder[11,14]	$ 1,030
i) environmentally controlled trailer[16,17,18,19] or cabinet to house items a,b,e,f,g,h	$ 4,890
j) sample probe backflush unit[11]	$ 1,480
TOTAL EQUIPMENT COSTS	$25,850
2. Installation Costs	
a) Installation[10,11,12,13]	$10,140
b) Initial Performance Specification Test[20]	$ 7,600
TOTAL INSTALLATION COST (includes initial performance specification test)	$17,740
TOTAL INSTALLED CAPITAL COST	$43,600

[a] May 1985 dollars.

TABLE 5-5. ANNUALIZED COSTS OF A CONTINUOUS NO_x MONITORING SYSTEM APPLICABLE TO FIRED HEATERS

Annualized Cost Component	Annualized Cost[a]
1. Direct Operating Costs	
a) operating labor for daily zero and span checks, routine maintenance[20]	$ 4,160/yr
b) operating labor for data handling and recording[20]	$ 5,270/yr
c) miscellaneous replacement parts[20]	$ 510/yr
d) NO_x calibration gases for daily zero and span checks[20]	$ 2,540/yr
TOTAL DIRECT OPERATING COSTS	$12,480/yr
2. Indirect Operating Costs	
a) overhead (80% of 1a + 1b)	$ 7,500/yr
b) property tax, insurance, administration (4% of capital cost)	$ 1,720/yr
c) capital recovery @ 10% rate of return, 8-year equipment lifetime (CRF = 0.1875)	$ 8,210/yr
d) semi-annual relative accuracy test for monitoring system[13]	$12,170/yr
TOTAL INDIRECT OPERATING COST	$29,600/yr
TOTAL ANNUALIZED COST	$42,080/yr

[a] May 1985 dollars.

5.4 SUMMARY OF CAPITAL AND ANNUALIZED COSTS

Capital and annual costs for LEA control, low-NO_x burners control and continuous NO_x emissions monitoring are summarized in Table 5-6. As shown in the table, LEA and NO_x monitoring capital and annualized costs are independent of heater size while low-NO_x burners control capital and annualized costs are a function of heater size. Also, LEA fuel credits are a function of heater size.

Table 5-6 also summarizes the capital and annualized costs for two control options. Control Option I includes LEA control and Control Option II includes LEA with low-NO_x burner control. The capital and annualized costs are also summarized for each control option with LEA fuel credits and with LEA fuel credits and NO_x monitoring.

Given the heater size, draft type, burner type, and NO_x emissions rate, the cost effectiveness of a control option can be calculated by first calculating the annualized cost and then dividing the annualized cost by the NO_x emissions reduction due to the control option. (See Chapter 4 for estimating NO_x reduction of the control technologies.) When LEA fuel credits are considered with the LEA control costs, the net result may be a cost benefit for the larger heaters. Finally, Control Option II is more costly than Control Option I, however, when the greater NO_x reduction is taken into consideration, Control Option II can be more cost effective for larger heaters that have conventional burners.

TABLE 5-6. SUMMARY OF CAPITAL AND ANNUALIZED COSTS OF THE CONTROL TECHNOLOGIES

Item	Capital Cost, 10^3\$	Annualized Cost, 10^3\$/yr
1. LEA Controls	36.3	11.0
2. LEA Fuel Credits		
ND	NA	-0.745
MD/AMB	NA	-0.707
MD/PH	NA	-0.605
3. Low-NO_x Burners	1.75 + 0.127 x S	0.285 + 0.0207 x S
4. Continuous NO_x Monitoring System	43.6	42.1
Control Option I (LEA Control)		
LEA Control	36.3	11.0
LEA Control with Fuel Credits		
ND	36.3	11.0 - 0.745 x S
MD/AMB	36.3	11.0 - 0.707 x S
MD/PH	36.3	11.0 - 0.605 x S
LEA Control with NO_x Monitoring and with Fuel Credits		
ND	79.9	53.1 - 0.745 x S
MD/AMB	79.9	53.1 - 0.707 x S
MD/PH	79.9	53.1 - 0.605 x S
Control Option II (LEA + Low-NO_x Burners Control)		
LEA and Low-NO_x Burners		
ND	38.1 + 0.127 x S	11.3 + 0.0207 x S
MD/AMB	38.1 + 0.127 x S	11.3 + 0.0207 x S
MD/PH	38.1 + 0.127 x S	11.3 + 0.0207 x S
LEA and Low-NO_x Burners Control with Fuel Credits		
ND	38.1 + 0.127 x S	11.3 - 0.724 x S
MD/AMB	38.1 + 0.127 x S	11.3 - 0.686 x S
MD/PH	38.1 + 0.127 x S	11.3 - 0.584 x S
LEA and Low-NO_x Burners Control with Fuel Credits and NO_x Monitoring		
ND	81.7 + 0.127 x S	53.4 - 0.724 x S
MD/AMB	81.7 + 0.127 x S	53.4 - 0.686 x S
MD/PH	81.7 + 0.127 x S	53.4 - 0.584 x S

[a] All costs in May 1985 dollars.

Notation: S = heater size, MMBtu/hr (absorbed duty).
NA = not applicable.

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APPENDIX A

FIRED HEATER ENERGY REQUIREMENT AND ENERGY REQUIREMENT GROWTH IN THE CHEMICAL INDUSTRY

In order to estimate the fired heater energy requirement and energy requirement growth in the chemical industry, chemical processes that use fired heaters and have the largest production rates were selected for evaluation. The chemicals were grouped according to those requiring high temperature heaters and those requiring low temperature heaters. The selected chemicals requiring high temperature heaters include methanol, ethylene, and ammonia and those requiring low temperature heaters include benzene, styrene, vinyl chloride, dimethyl terephthalate (DMT/PTA), p-xylene, acetone, and butadiene.

The most recent production data was obtained for these chemicals for 1984 from the "Top 50 Chemical" listing of Chemical and Engineering News. Capacity utilization information for 1984 was also obtained from "Capacity Utilization for Basic Chemicals" listing of Chemical and Engineering News. Growth projection estimates for the years 1985 - 1989 were obtained from "chemical profiles" from Chemical Marketing Reporter.

The production for 1985 for each chemical was estimated using the growth rates for each chemical. These are shown in Table 3-12. Also shown in Table 3-12 are the heat requirements for the selected chemicals. The projected fired heater energy for 1985 was calculated by multiplying the heat requirements by the 1985 prediction production for each chemical.

To calculate the growth in the energy requirement for the chemical industry, the production rate for each chemical was predicted for each year through 1989. The capacity utilization was also calculated for each year for each chemical. Then, for those chemicals whose capacity utilization went above 82 percent, the increase in production was considered to require new construction of the chemical process which would include new fired heaters. For those chemicals requiring new construction, the increase in production was converted to an energy requirement using the fired heater energy requirements in Table 3-12. The chemicals that showed an increase in production requiring new construction included styrene, p-xylene, ethanol, methanol, ethylene, and ammonia.

An example calculation is shown below for methanol:

Given:

1984 Production = 8.28×10^9 lb/yr

Capacity Utilization in 1984 = 74%

Estimated Growth Rate = 6%/yr

Heat Requirement = 3.3×10^3 Btu/lb feed

In 1985: Production = 8.28×10^9 lb (1.06) = 8.78×10^9 lb/yr

$$\text{Capacity Utilization} = \frac{8.78 \times 10^9 \ (0.74)}{8.28 \times 10^9} = 0.78$$

Fired Heater Energy Requirement = (8.78×10^9 lb/yr) x (3.3×10^3 Btu/lb feed) = 73.9×10^{12} Btu/yr

For the years 1986 to 1989:

In 1986: Production = $8.28 \times 10^9 \ (1.06)^2$ = 9.30×10^9 lb/yr

$$\text{Capacity Utilization} = \frac{9.30 \times 10^9 \text{ lb/yr } (0.74)}{8.28 \times 10^9 \text{ lb/yr}} = 0.83$$

(1987 - 1989 calculated similarly)

So starting in 1986, for methanol, new production will require new construction as the capacity utilization goes over 82 percent. Thus, new production requiring new construction converted to energy requirement is:

For methanol, new 1986 increase in energy requirement:

[production in 1986 - production in 1985] x heat requirement =

[8.78 x 10^9 lb/yr - 8.28 x 10^9 lb/yr] 3.3 x 10^3 Btu/lb feed =

1.72 x 10^{12} Btu/yr

The percent increase in fired heater energy requirement was calculated by dividing the increase of the energy requirement requiring new construction by the total energy requirement for 1985. The growth rate was estimated to be the same for each year in the period 1985 to 1989. An example calculation is shown for methanol for the year 1986:

$$100 \times \frac{\text{increase in energy requirement in 1986} = 1.72 \times 10^{12}\ \text{Btu/yr}}{\text{energy requirement in 1985} = 73.9 \times 10^{12}\ \text{Btu/yr}}$$

= 2.3% increase in energy for 1986

To calculate the number of new heaters, the increase in energy requirement was divided by the average heater size. The average heater size for low temperature heaters was 15 MM Btu/hr and for high temperature heaters was 350 MM Btu/hr. An example calculation is shown for methanol for the year 1986.

$$\frac{[\text{increase in energy requirement in 1986} = 1.72 \times 10^{12}\ \text{Btu/yr}]}{[\text{average high temperature heater size} = 350 \times 10^{6}\ \text{Btu/hr}] \times 8{,}400\ \text{hrs/yr}}$$

= 0.6 new methanol heaters in the year in 1986

APPENDIX B. EXAMPLE DATA SHEETS FOR HEATERS IN LONG TERM DATA BASE

TABLE B-1

USA PETROCHEM DATA

NOx HOURLY READINGS

SEP 1 1 1976

TIME	STEP #2 REFORMER					STEP #1 DESULFURIZER					STEP #3 CRUDE					Total lb/hr
	NO_x	02	F/G	lb/hr	Comments	NO_x	O_2	F/G	lb/hr	Comments	NO_x	02	F/G	lb/hr	Comments	
6 am	55	3.2	3.5	3.91		41	13.1	1.3	.93		74	.9	8.2	6.29		11.14
7 am	55	3.1	3.6	4.02		41	13.1	1.3	.93		75	.8	8.2	6.35		11.31
8 am	41	3.1	3.5	3.62		41	12.8	1.3	.90		76	1.1	8.1	6.44		10.96
9 am	55	3.4	3.5	3.95		41	13.5	1.3	.98		75	1.2	8.1	6.38		11.32
10 am	54	3.2	3.5	3.85		41	13.4	1.3	.97		74	1.2	8.1	6.30		11.11
11 am	49	3.0	3.6	3.57		40	12.7	1.3	.87		20	1.3	8.3	6.13		10.57
Noon	46	2.8	3.6	3.32		37	12.5	1.3	.81		67	1.2	8.4	5.91		10.04
1 pm	45	2.8	3.6	3.25		37	12.7	1.3	.81		66	1.3	8.4	5.85		9.91
2 pm	46	2.8	3.6	3.32		36	12.4	1.3	.76		66	1.2	8.4	5.82		9.90
3 pm	44	2.5	3.7	3.24		37	12.2	1.3	.76		67	1.2	8.4	5.91		9.91
4 pm	43	2.3	3.7	3.13		35	12.2	1.3	.72		65	1.0	8.4	5.69		9.55
5 pm	48	3.0	3.8	3.68		36	11.8	1.4	.77		64	.8	8.3	5.49		9.94
6 pm	40	2.2	3.8	2.93		37	11.8	1.5	.85		65	.8	8.3	5.58		9.35
7 pm	45	2.2	3.6	3.13		36	11.8	1.4	.77		73	1.0	8.0	6.09		9.98
8 pm	53	3.0	3.6	3.82		40	12.8	1.4	.95		80	1.0	7.8	6.50		11.27
9 pm	60	3.8	3.6	4.49		43	13.2	1.4	1.07		80	1.3	7.8	6.58		12.14
10 pm	55	3.0	3.6	4.00		45	13.0	1.3	1.01		85	1.2	7.8	6.97		11.99
11 pm	59	3.1	3.6	4.32		45	13.4	1.3	1.06		90	1.3	7.8	7.41		12.79
Mid	60	3.0	3.6	4.42		47	13.3	1.2	1.01		84	.5	7.9	6.77		12.21
1 am	57	2.5	3.4	3.84		47	13.2	1.2	1.00		85	1.0	7.6	6.73		11.58
2 am	60	3.2	3.5	4.32		47	13.1	1.2	.98		82	.8	7.9	6.69		12.01
3 am	60	3.8	3.6	4.38	NOx pattern is scattered	47	13.2	1.2	1.00		83	.7	7.6	6.49	Nox pattern scattered	11.87
4 am	62	2.9	3.5	4.40	"	47	13.0	1.2	.97		83	.7	7.6	6.49	"	11.87
5 am	60	3.5	3.6	4.52	"	48	13.2	1.2	1.02		82	.8	7.9	6.69	"	12.24
	A	B	D			A	B	C			A	B	E			2nd-A

8-4 CG

4-12

12-8

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TABLE B-2

GETTY REFINING DATA

MOHAWK PETROLEUM CO. — GRMC
BAKERSFIELD REFINERY
NORTH PLANT
HOURLY EMISSIONS REPORT
OCTOBER 10, 1980

		FUEL BURNED					EMISSIONS (LB/HR)				
		FUEL GAS		FUEL OIL		TOTAL	NO2	NO2	SO2	part.	O2
TIME	HEATER NO.	MSCFH	MM Btu/Hr	B/D	MM Btu/Hr	MM Btu/Hr	Firebox	stack			%
15:10	8-H1	12.55	16.98	0.00	0.00	16.98	3.40	3.40	0.00	0.17	7.44
	8-H2	14.40	19.57	0.00	0.00	19.57	3.91	3.91	0.00	0.20	1.00
	9-H1-4	98.89	133.74	0.00	0.00	133.74	36.75	11.93	0.06	1.34	7.36
	9-H5	8.09	10.93	0.00	0.00	10.93	2.19	2.19	0.01	0.11	9.52
	10-H1	45.32	61.29	269.20	9.02	130.30	39.86	0.39	36.67	6.13	1.00
	11-H1	43.43	58.73	35.84	9.19	67.92	15.42	3.10	4.91	1.32	2.85
	12-H1	27.74	37.52	8.05	2.06	39.58	8.33	2.68	1.11	0.54	5.63
	14-H1	16.49	22.28	0.18	0.05	22.32	4.47	1.22	0.04	0.23	7.83
	81-H1	24.56	33.19	62.71	16.08	49.27	13.07	10.33	8.55	1.62	2.07
	81-H2	21.36	28.86	71.25	18.27	47.13	13.08	11.16	9.71	1.75	2.16
TOTAL NEW PLANT		312.91	423.09	447.23	114.66	537.75	130.48	50.31	61.07	13.40	4.69
TOTAL REFINERY		341.91	462.31	447.23	114.66	576.97	140.01	59.84	61.07	15.16	

FUEL CHARACTERISTICS

FUEL GAS					FUEL OIL							
% H2	Sp.Gr	PPM	Gr/dscf	Btu/SCF	K	C/H	MM Btu/bbl	Wt % S	Wt % N	Wt % H2O	Wt % ASH	API Gravity
35.0	0.75	3.9	0.002	1352.0	11.8	7.7	6.152	0.49	0.67	0.00	0.20	16.9

Incinerator 16-M-101: SO2- 40. PPM, O2- 4.6 %, 11-V-2 Off gas H2S-0.000 Gr/DSCF, Flare discharge-24.49 MLB/HR.

Wind Speed 32.5 MPH from N .

Table B-3. Sample Data Sheet from U.S. EPA/IERL Long Term CEM Data

PETROLEUM PROCESS HEATER: LOW NOX BURNERS
15 MIN. DATA
DRY STACK GAS CONCENTRATION

DATE	TIME	LOAD B/D	O2 VOL% MEAS	CO2 VOL% MEAS	CO PPMV MEAS	NO PPMV MEAS	CO PPMV 3%O2	NO PPMV 3%O2	CO NG/J	NO NG/J	ACODE
8/ 3/81	1215	7920.0	5.6	8.6	7	78	8	91	2	49	
8/ 3/81	1230	7920.0	5.8	8.5	7	78	8	92	2	50	
8/ 3/81	1245	7920.0	6.0	8.4	6	78	7	93	2	50	
8/ 3/81	1300	7920.0	5.9	8.5	6	79	7	94	2	51	
8/ 3/81	1315	7920.0	6.1	8.3	6	78	7	94	2	51	
8/ 3/81	1330	7920.0	6.1	8.3	6	79	7	95	2	51	
8/ 3/81	1345	7920.0	6.0	8.4	6	79	7	94	2	51	
8/ 3/81	1400	.0	.0	.0	0	0	0	0	0	0	C
8/ 3/81	1415	.0	.0	.0	0	0	0	0	0	0	C
8/ 3/81	1430	7920.0	4.0	9.6	8	83	8	87	2	47	
8/ 3/81	1445	7920.0	4.6	9.2	8	84	8	92	2	50	
8/ 3/81	1500	7920.0	5.6	8.6	26	83	30	97	10	52	
8/ 3/81	1515	7920.0	2.0	10.1	21	80	19	75	6	41	
8/ 3/81	1530	7920.0	2.2	10.7	29	81	27	77	9	42	
8/ 3/81	1545	7920.0	2.6	10.8	10	85	9	83	3	45	
8/ 3/81	1600	.0	.0	.0	0	0	0	0	0	0	C
8/ 3/81	1615	.0	.0	.0	0	0	0	0	0	0	I
8/ 3/81	1630	.0	.0	.0	0	0	0	0	0	0	I
8/ 3/81	1645	7920.0	3.5	10.1	7	88	7	90	2	49	
8/ 3/81	1700	7920.0	3.3	10.1	17	75	17	76	5	41	
8/ 3/81	1715	7920.0	4.0	9.7	6	77	6	81	2	44	
8/ 3/81	1730	7920.0	4.1	9.6	6	76	6	80	2	43	
8/ 3/81	1745	7920.0	4.0	9.7	6	77	6	81	2	44	
8/ 3/81	1800	7920.0	3.6	9.9	8	76	8	78	2	42	
8/ 3/81	1815	7920.0	3.6	9.9	7	76	7	78	2	42	
8/ 3/81	1830	7920.0	4.3	9.5	7	77	7	83	2	45	
8/ 3/81	1845	7920.0	4.5	9.4	6	77	6	84	2	45	
8/ 3/81	1900	7920.0	4.5	9.4	6	77	6	84	2	45	
8/ 3/81	1915	7920.0	4.7	9.3	7	77	7	85	2	46	
8/ 3/81	1930	7920.0	4.6	9.3	7	77	7	84	2	45	
8/ 3/81	1945	7920.0	4.4	9.4	7	78	7	84	2	45	
8/ 3/81	2000	7920.0	4.3	9.5	8	78	8	84	2	45	
8/ 3/81	2015	7920.0	4.1	9.6	8	77	8	82	2	44	
8/ 3/81	2030	7920.0	4.1	9.6	8	77	8	82	2	44	
8/ 3/81	2045	7920.0	3.6	9.9	9	77	9	79	3	43	
8/ 3/81	2100	7920.0	3.7	9.9	10	77	10	80	3	43	
8/ 3/81	2115	7920.0	3.6	9.9	10	78	10	80	3	43	
8/ 3/81	2130	7920.0	3.8	9.8	10	77	10	80	3	43	
8/ 3/81	2145	7920.0	3.3	10.1	10	77	10	78	3	42	
8/ 3/81	2200	7920.0	3.3	10.1	10	78	10	79	3	43	
8/ 3/81	2215	7920.0	3.7	9.9	10	79	10	82	3	44	
8/ 3/81	2230	7920.0	3.5	10.0	9	78	9	80	3	43	
8/ 3/81	2245	7920.0	3.5	10.0	10	79	10	81	3	44	
8/ 3/81	2300	7920.0	3.6	9.9	10	79	10	81	3	44	
8/ 3/81	2315	7920.0	3.9	9.8	10	81	10	85	3	46	
8/ 3/81	2330	7920.0	3.7	9.9	9	80	9	83	3	45	
8/ 3/81	2345	7920.0	3.8	9.9	9	81	9	84	3	45	
8/ 3/81	2400	7920.0	3.8	9.9	9	82	9	85	3	46	

C = Instrument Calibrations
I = Continuous Monitor Certification Tests

APPENDIX C

STATISTICAL PROCEDURES FOR MODELING

Mathematical models of NO_x emissions were developed for each heater using the AUTOREG procedure of the Statistical Analysis System (SAS). These autoregressive models examined the effects of stack oxygen level, heater load, oil-to-gas ratio (when applicable), and gas fuel H_2 content (for the Getty heaters) on NO_x emissions. These models also accounted for any effects of autocorrelation, due to the sequential nature of the data, on the coefficients obtained. The AUTOREG procedure only operated with additive model forms. In order to determine the coefficients for the multiplicative models given in Section 4.3.1, the data were transformed by taking natural logarithms.

The implementation of the AUTOREG procedure required complete data for both the dependent variable (NO_x emissions) and the independent variables (stack oxygen level, heater load, oil-to-gas ratio, and H_2 content). It was thus necessary to estimate missing values of the different parameters for each heater.

An iterative technique was used to supply missing data. For each heater and variable, the missing values in the sequence were first replaced by the mean of the nonmissing data in the series. An autoregressive model was fitted to this series using the ARIMA procedure of SAS. In the following iterations, missing values were replaced by values estimated with the model given by the ARIMA procedure in the previous iteration. Convergence was assumed when the model estimates and the residual sums of squares stabilized.

Once the missing data were estimated, the autoregressive models were developed for each heater by the AUTOREG procedure. Table 4-4 gave the coefficients obtained for each heater model, as well as 95 percent confidence intervals for each coefficient. Also included in the table are the coefficients of determination (R^2) values for each model. R^2 values can vary between 0 and 1, with higher values indicating better fit. As seen, in the table, good fit was obtained for each model, as R^2 values ranged from 0.70 to 0.95. These R^2 values were based only on the actual data points, not on the estimated missing data.

Also, Table 4-4 shows that for each heater the exponent for stack oxygen level, c_3, is always positive and that the 95 percent confidence intervals do not approach zero. Thus, stack oxygen level appears to be an important parameter in determining NO_x emissions, with increases in stack oxygen yielding generally higher NO_x emissions.

APPENDIX D

CONVERSION FACTORS

1 MMBtu = 10^6 Btu

1 Btu = 1054.2 Joules = 0.252 kcal

1 lb = 0.454 kg

1 lb/MM Btu = 430 ng/J

1 MMBtu/hr = 0.2929 MW_t

1 in water = 4.015 kPa